# *The University of Tennessee*

## Energy Efficient Thermal Management of Natural Gas Engine Aftertreatment Via Active Flow Control

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**COOPERATIVE AGREEMENT DE-FC26-02NT41609**

**Awarded (10/01/2002, 36 Month Duration)**

**$750,000 Total Contract Value ($600,000 DOE)**

**2005 ARES University Peer Review     Argonne National Laboratory**

**July 12, 2005**

# Meeting ARES Goals with NOx Adsorber Technology

**$\eta$ = 50%**

High efficiency typically requires a lean air-fuel mixture

**NOx = 0.10 g/hp-hr**

NOx reduction typically requires a rich air-fuel mixture

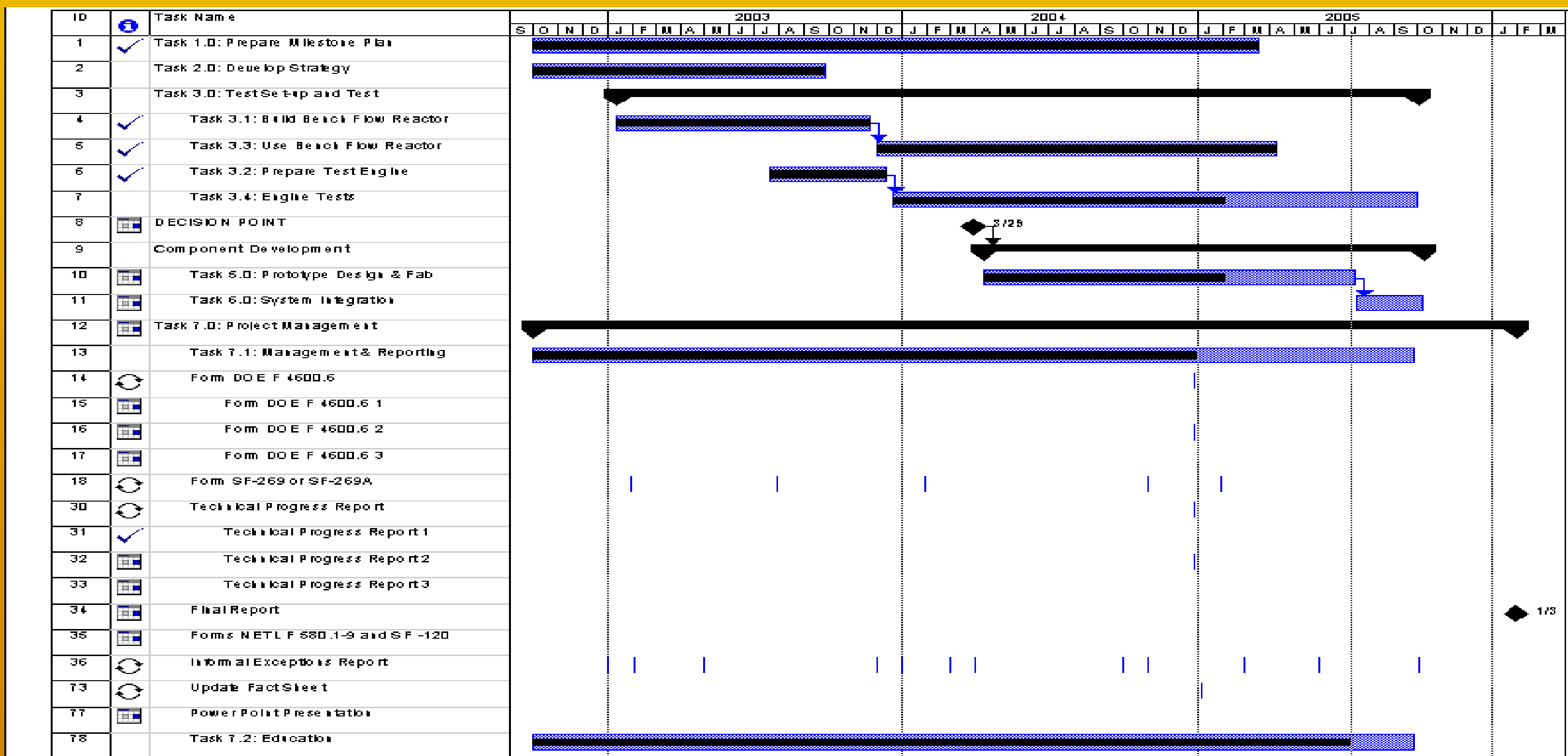
**NOx Adsorbing Catalyst**

Unlike typical 3-way catalysts, NOx adsorbers allow for lean-burn operation as well as NOx reduction

# Project Objectives

- Reduce $NO_x$ and $CH_4$ emission by 90% from lean burn natural gas engines
- Reduce supplemental fuel use by 50-70%
- Reduce catalyst costs
- Manage exhaust energy

# Schedule



ID
Task Name
2003
2004
2005
1 Task 1.0: Prepare Milestone Plan
2 Task 2.0: Develop Strategy
3 Task 3.0: Test Setup and Test
4 Task 3.1: Build Bench Flow Reactor
5 Task 3.3: Use Bench Flow Reactor
6 Task 3.2: Prepare Test Engine
7 Task 3.4: Engine Tests
8 DECISION POINT
9 Component Development
10 Task 5.0: Prototype Design & Fab
11 Task 6.0: System Integration
12 Task 7.0: Project Management
13 Task 7.1: Management & Reporting
14 Form DOE F 4600.6
15 Form DOE F 4600.6 1
16 Form DOE F 4600.6 2
17 Form DOE F 4600.6 3
18 Form SF-269 or SF-269A
30 Technical Progress Report
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34 Final Report
35 Forms NETL F 580.1-9 and SF-120
36 Informal Exceptions Report
73 Update Fact Sheet
77 PowerPoint Presentation
78 Task 7.2: Education
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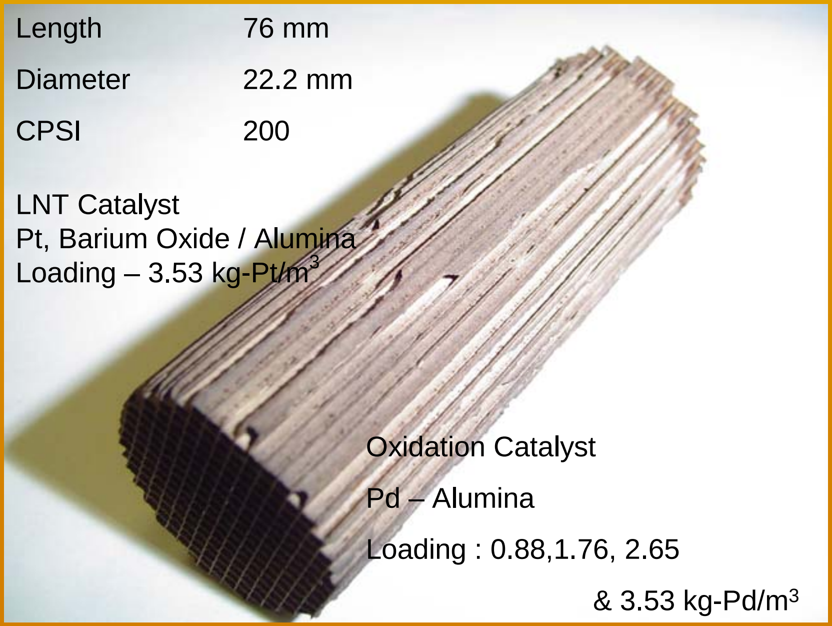
# Technical Approach

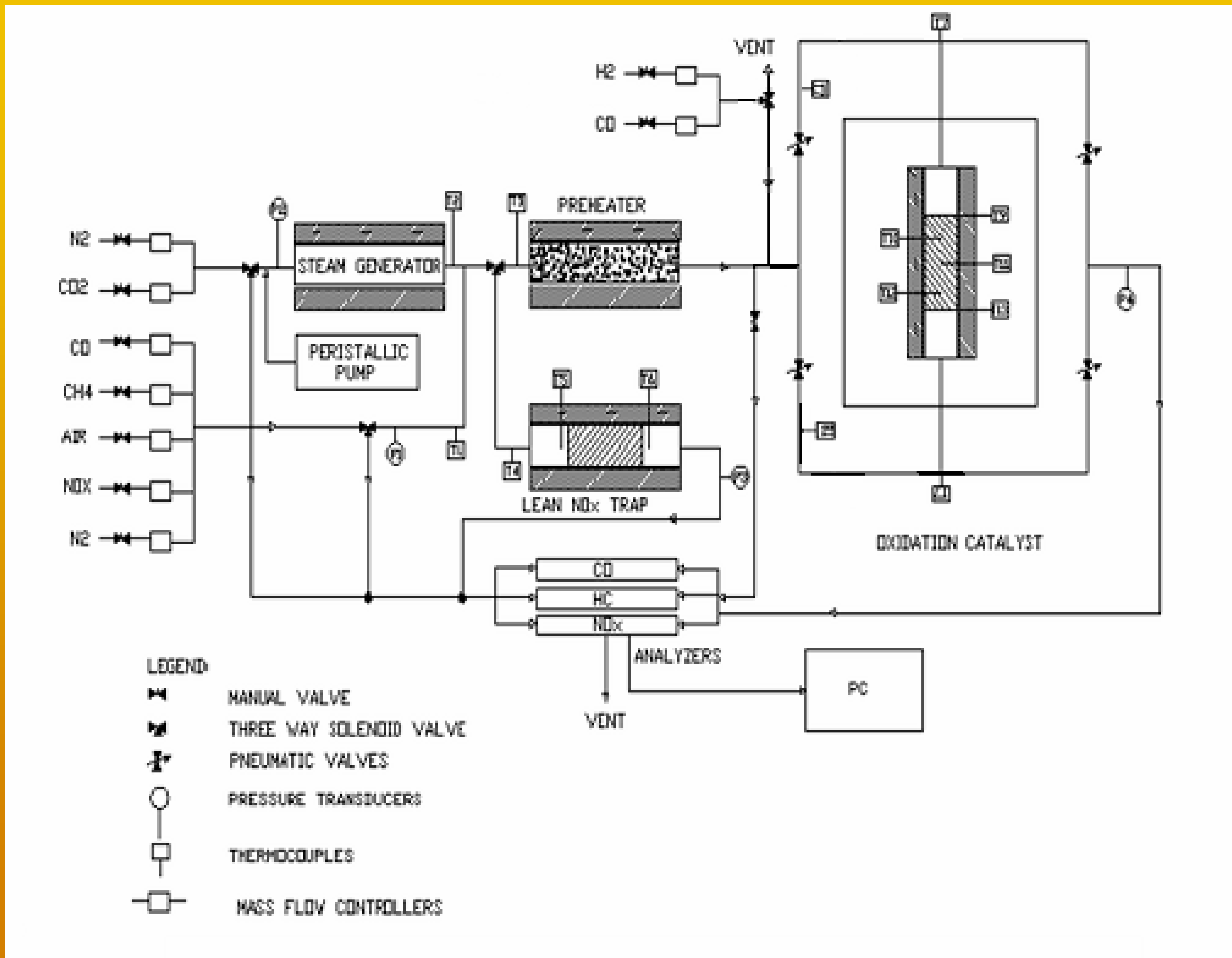
- Partial flow restriction for regeneration and desulfurization of NOx adsorber
- Alternating between regeneration and adsorption for NOx adsorber
- Periodic flow reversal for oxidation catalyst
- Supplemental fuel injection for regeneration and desulfurization of NOx adsorber and for maintaining light-off of oxidation catalyst

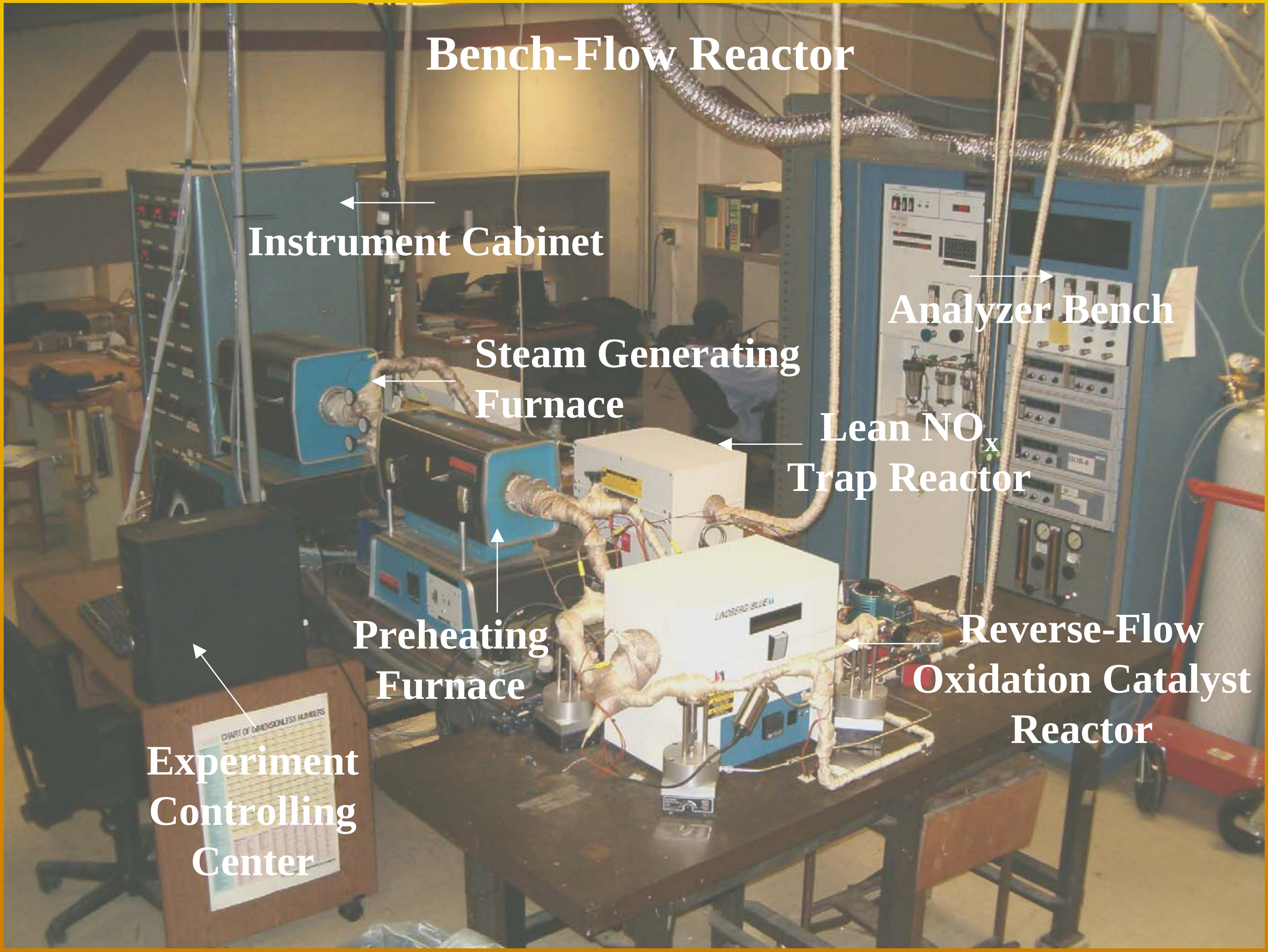
# Bench Flow Reactor

- Reverse Flow Oxidation Catalyst System Evaluation
- Lean NOx Trap Evaluation and Optimization



# Schematic of the Bench-Flow Reactor System




Bench-Flow Reactor
Instrument Cabinet
Analyzer Bench
Steam Generating Furnace
Lean $NO_x$ Trap Reactor
Preheating Furnace
Reverse-Flow Oxidation Catalyst Reactor
Experiment Controlling Center

# Reverse Flow Oxidation Catalyst System Evaluation

## Accomplishments

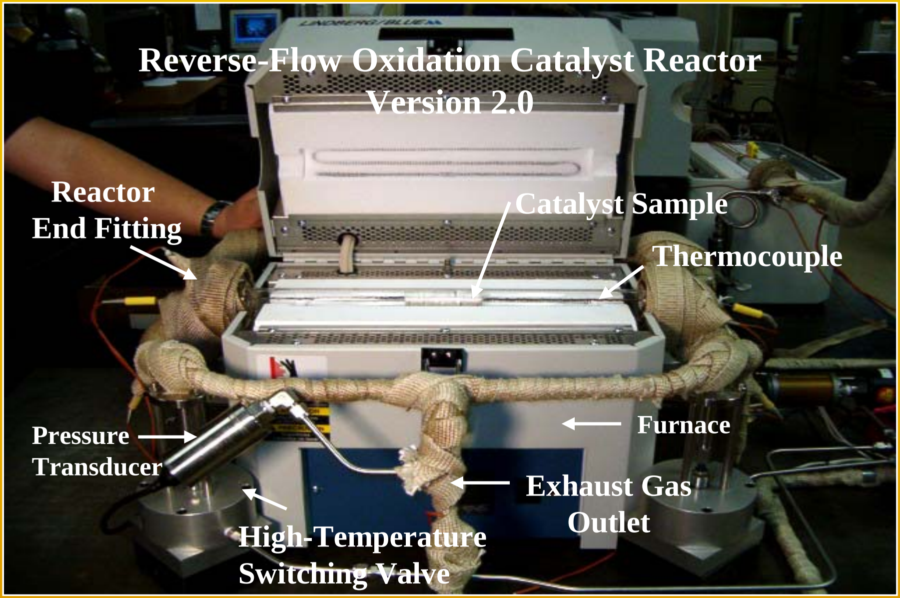
- Reverse-Flow Oxidation Catalyst Reactor Characterization Matrix

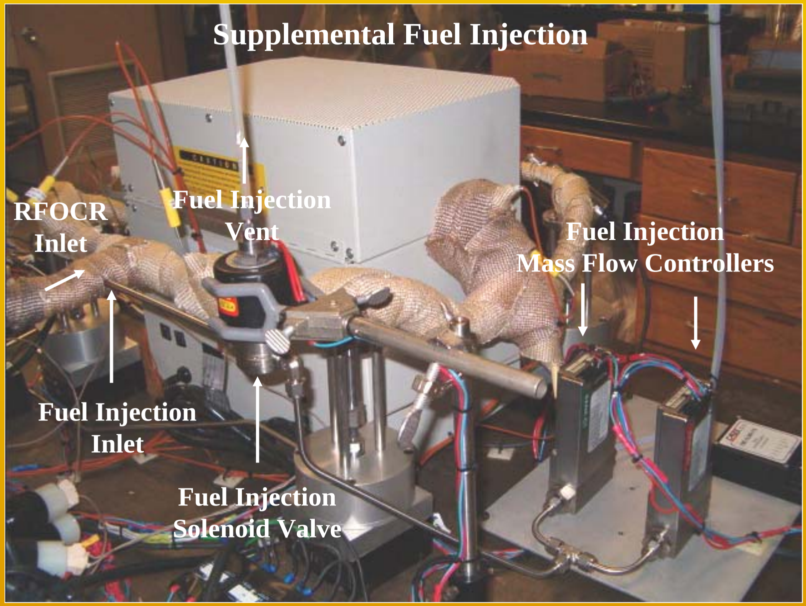
| | 400°C | 450°C | 500°C | 550°C | 600°C |
|---|---|---|---|---|---|
| 20,000 hr$^{-1}$ | √ | √ | √ | √ | **N/A** |
| 40,000 hr$^{-1}$ | √ | √ | √ | √ | **N/A** |
| 60,000 hr$^{-1}$ | √ | √ | √ | √ | **N/A** |
| 80,000 hr$^{-1}$ | **N/A** | √ | √ | √ | √ |

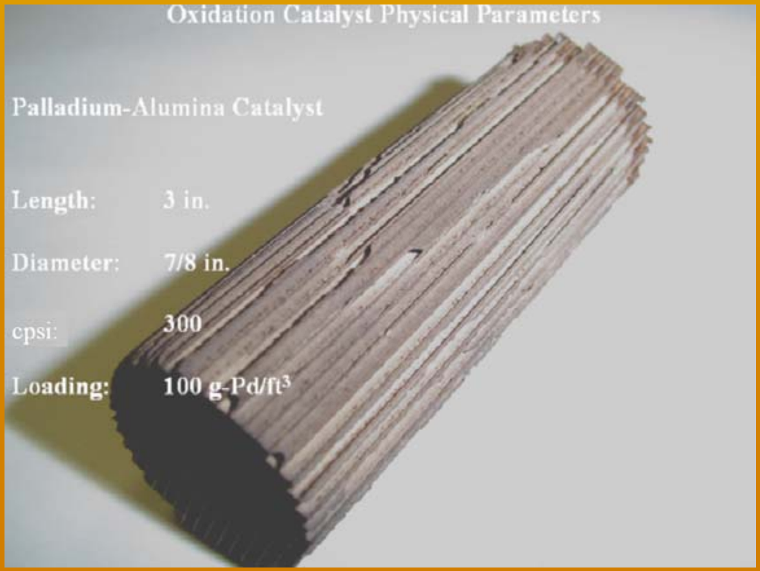
Switching Time: 10, 15, 20, 30, and 45 seconds

- Supplemental fuel injection evaluation at 350°C, SV = 20,000 hr$^{-1}$

# Experimental Setup

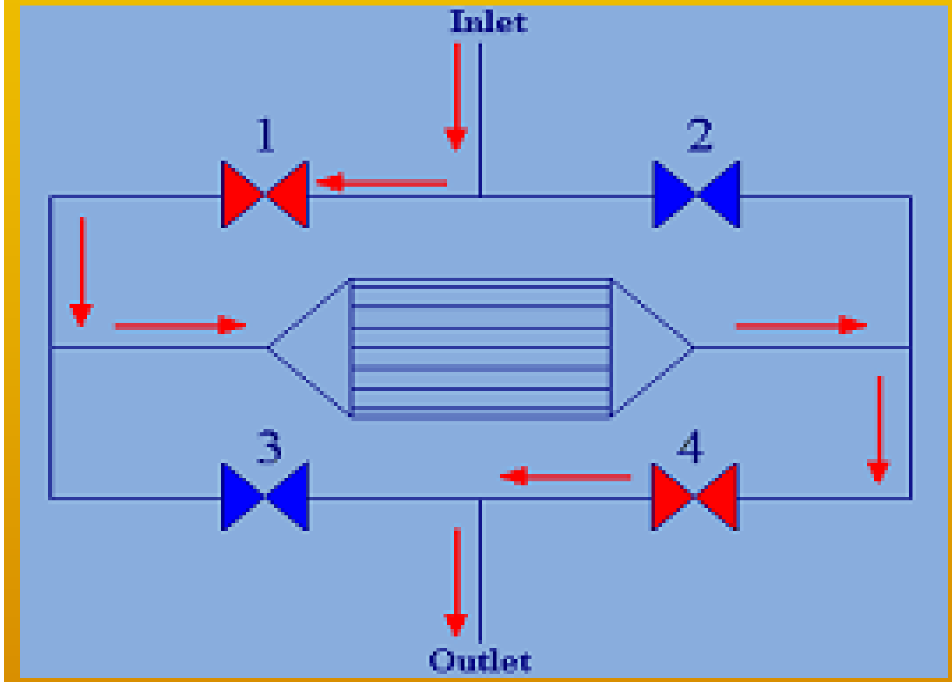


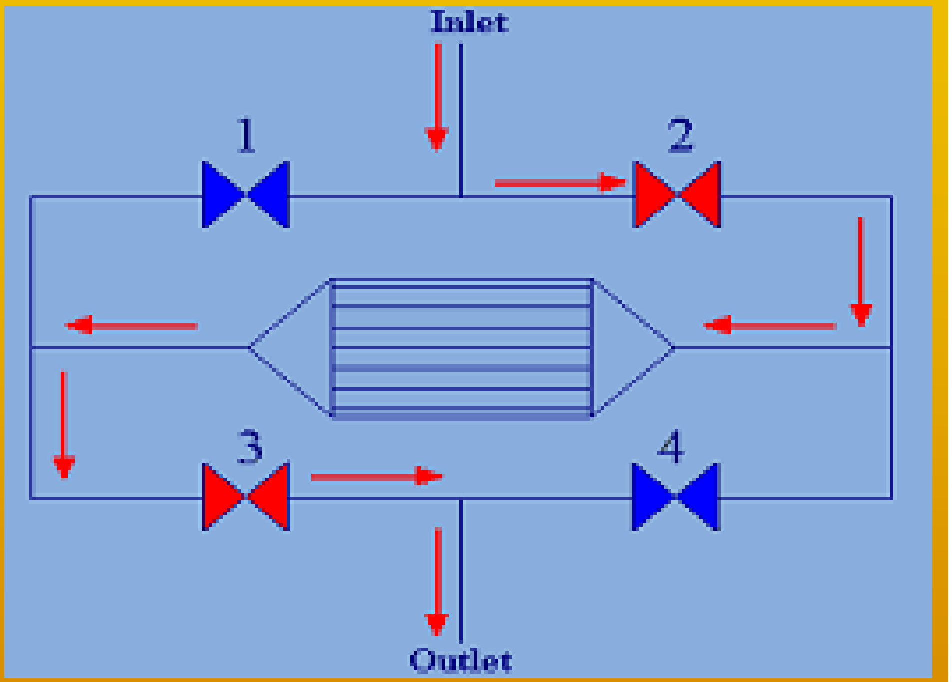




| | |
|---|---|
| NOx | 0 |
| $H_2$ | 0 |
| CO | 0.5% |
| $CH_4$ | 2000 ppm |
| $CO_2$ | 6% |
| $H_2O$ | 10% |
| $O_2$ | 6% |
| $N_2$ | Balance |

# Operation of the Reverse-Flow Oxidation Catalyst Reactor



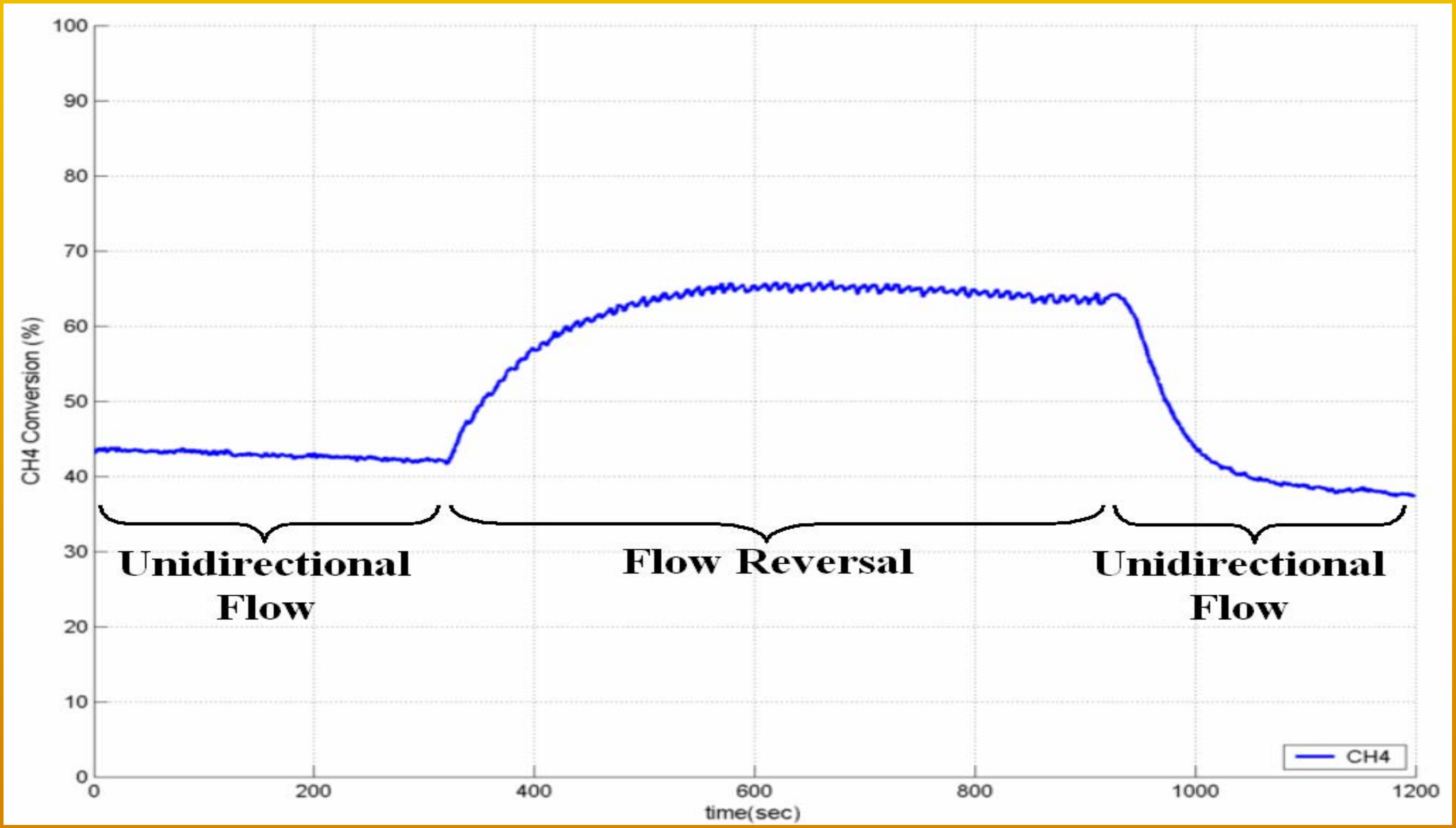
Forward Flow



Reverse Flow

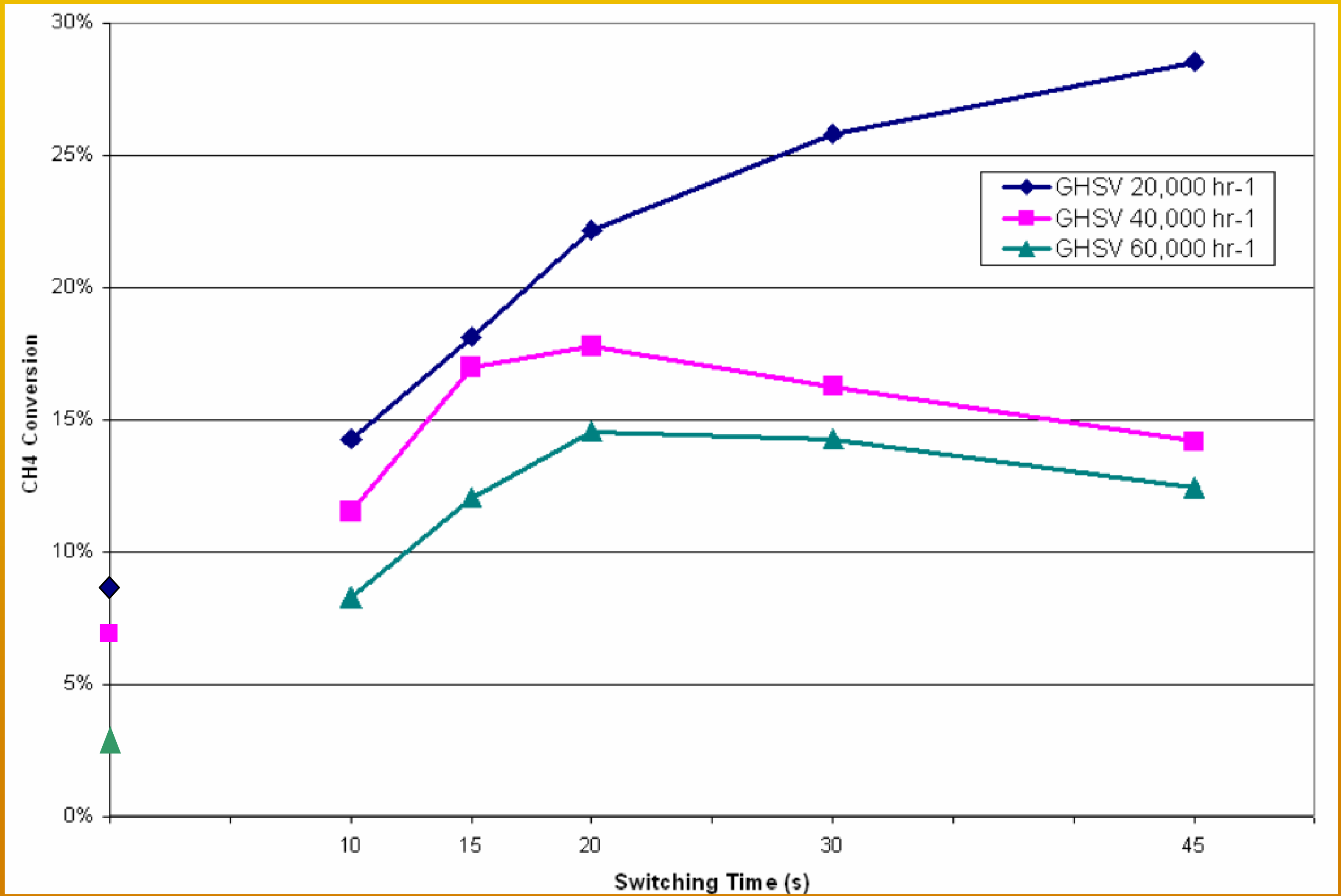
- Symmetrical switching time is defined as duration in the forward flow being equal to the reverse flow
- Unsymmetrical switching time is defined as the duration in the forward flow being different than the reverse flow

# Reverse Flow Operation



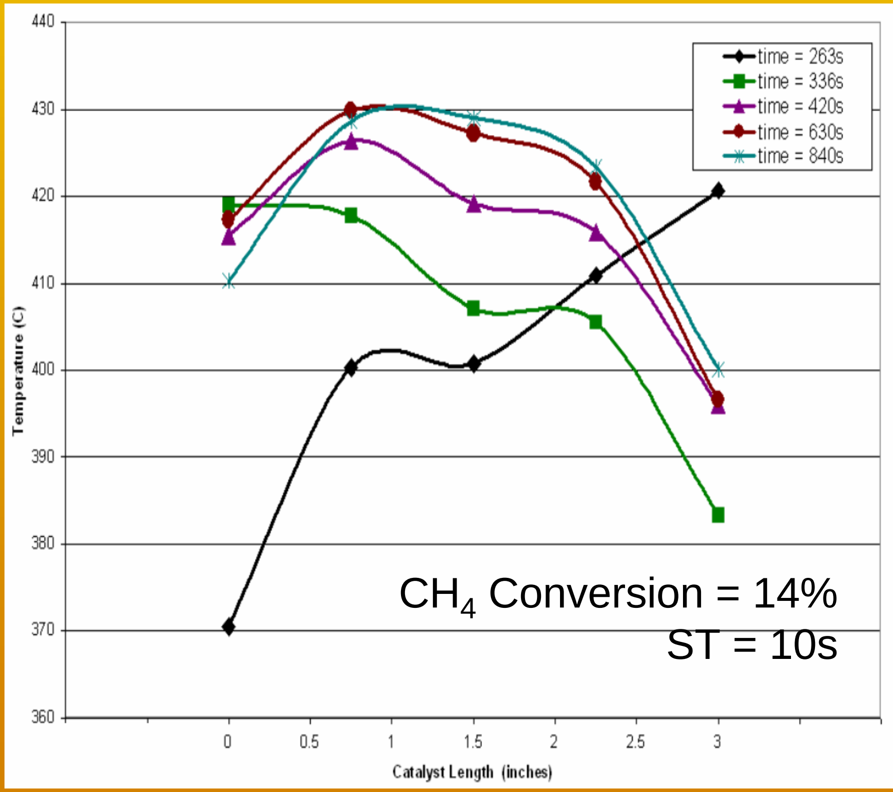
# Methane Conversion

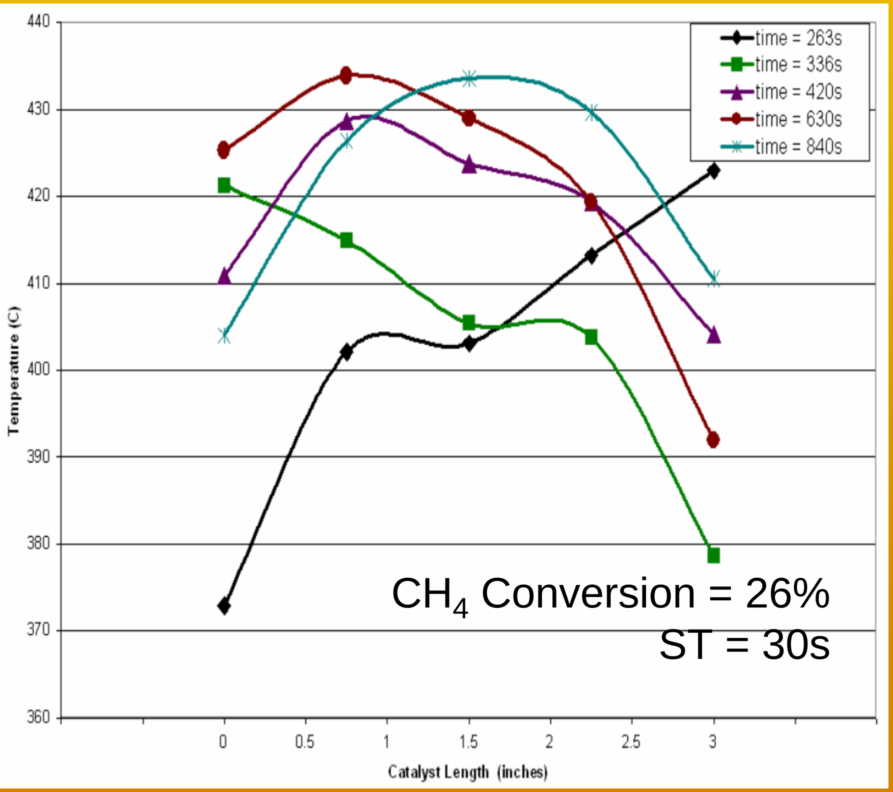
Furnace Temperature = 400°C



# Temperature Profile

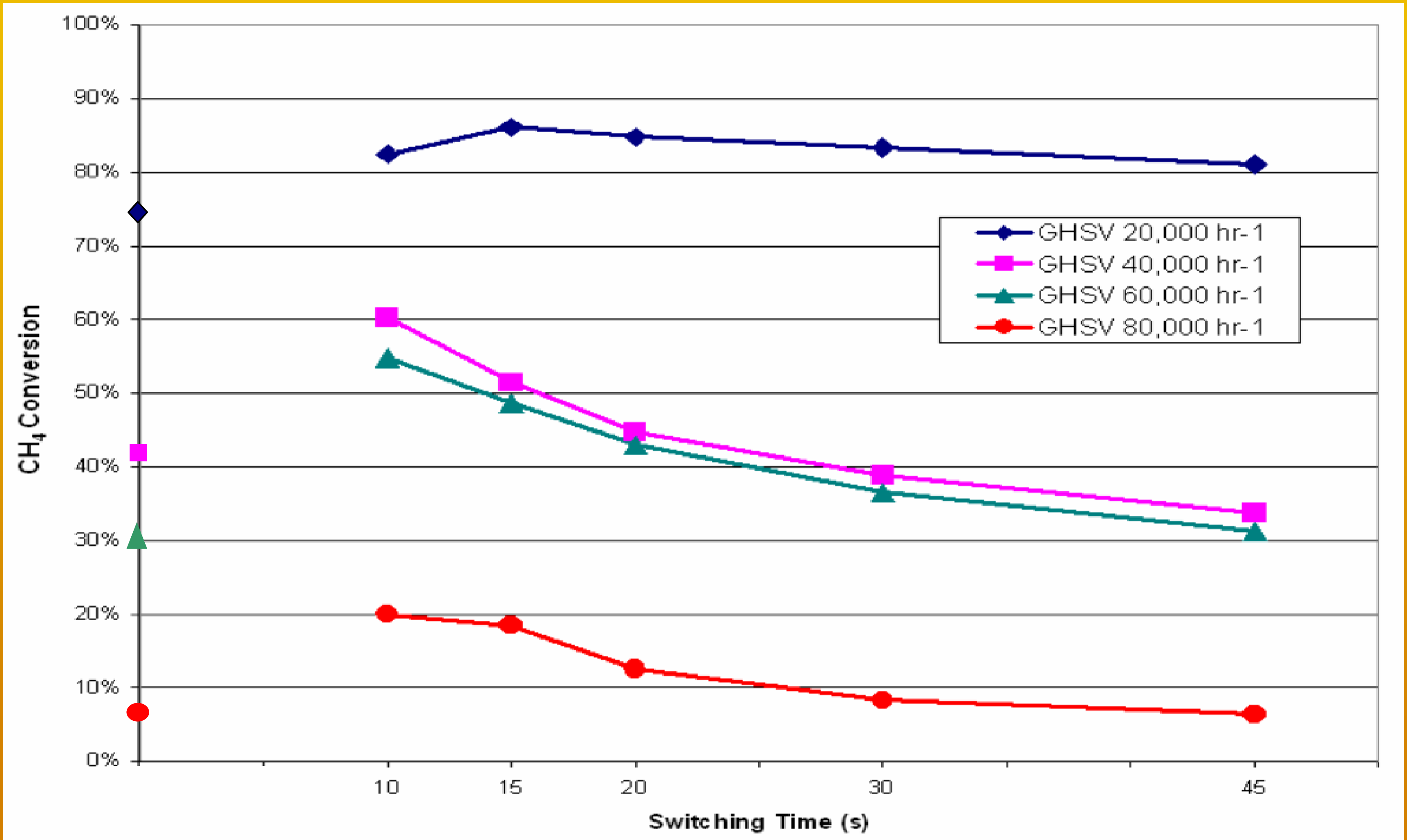
Furnace Temperature = 400°C
GHSV = 20,000 $hr^{-1}$



# Methane Conversion

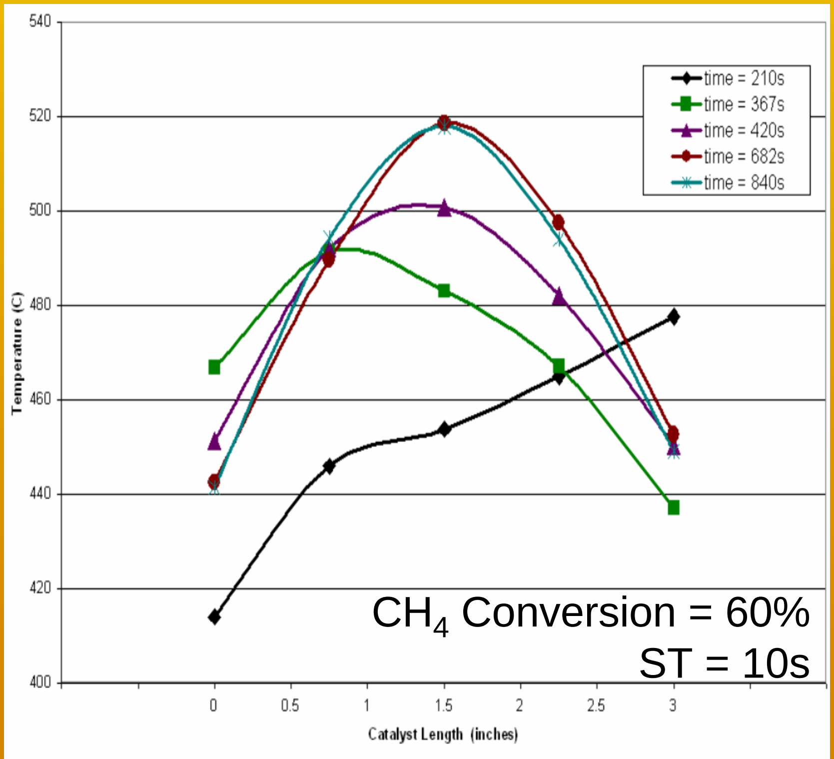
Furnace Temperature = 450°C

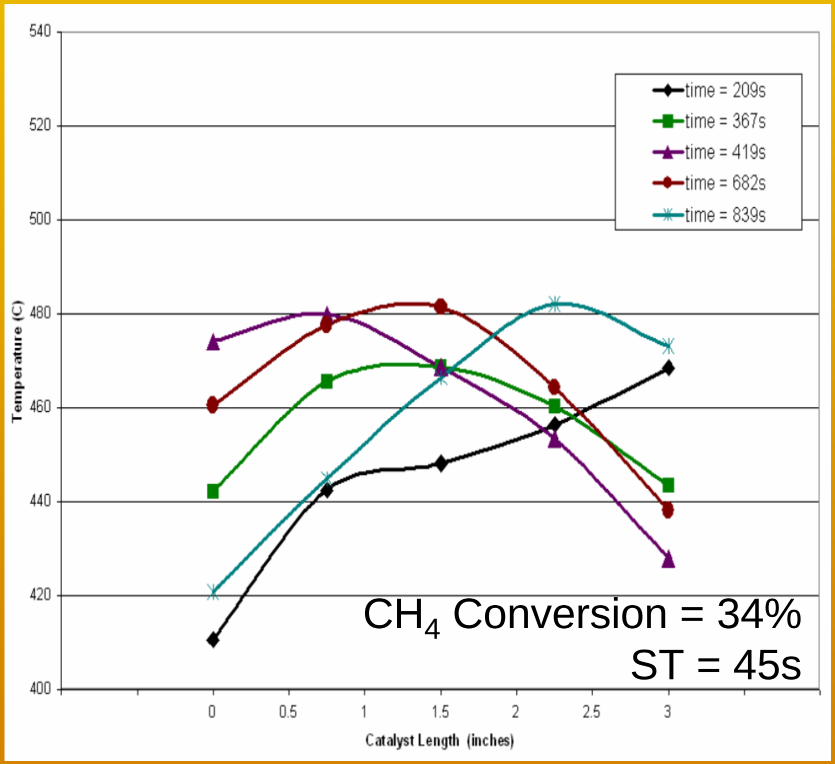


# Temperature Profile

Furnace Temperature = 450°C

GHSV = 40,000 $hr^{-1}$



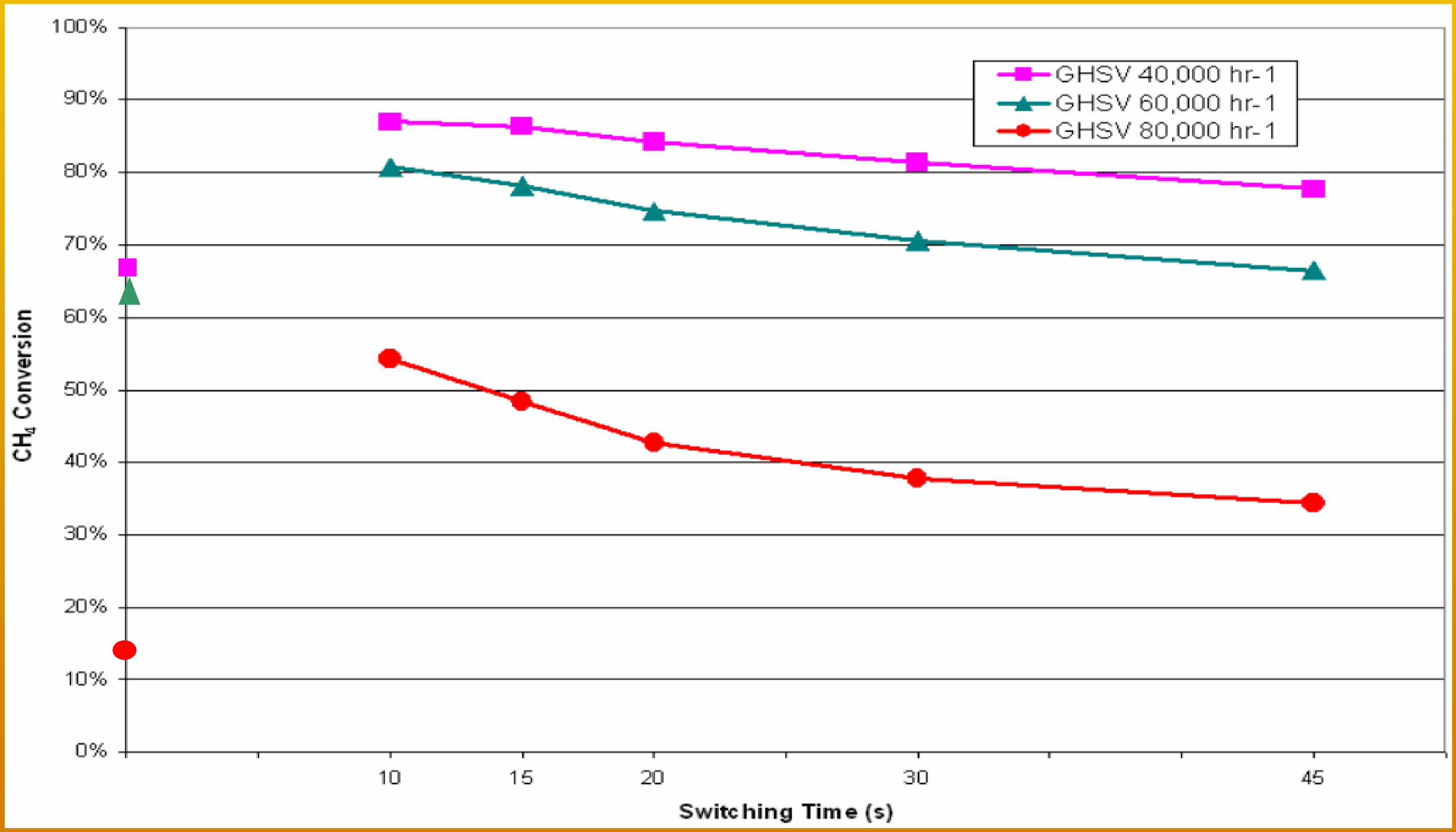




$CH_4$ Conversion = 60%
ST = 10s

$CH_4$ Conversion = 34%
ST = 45s

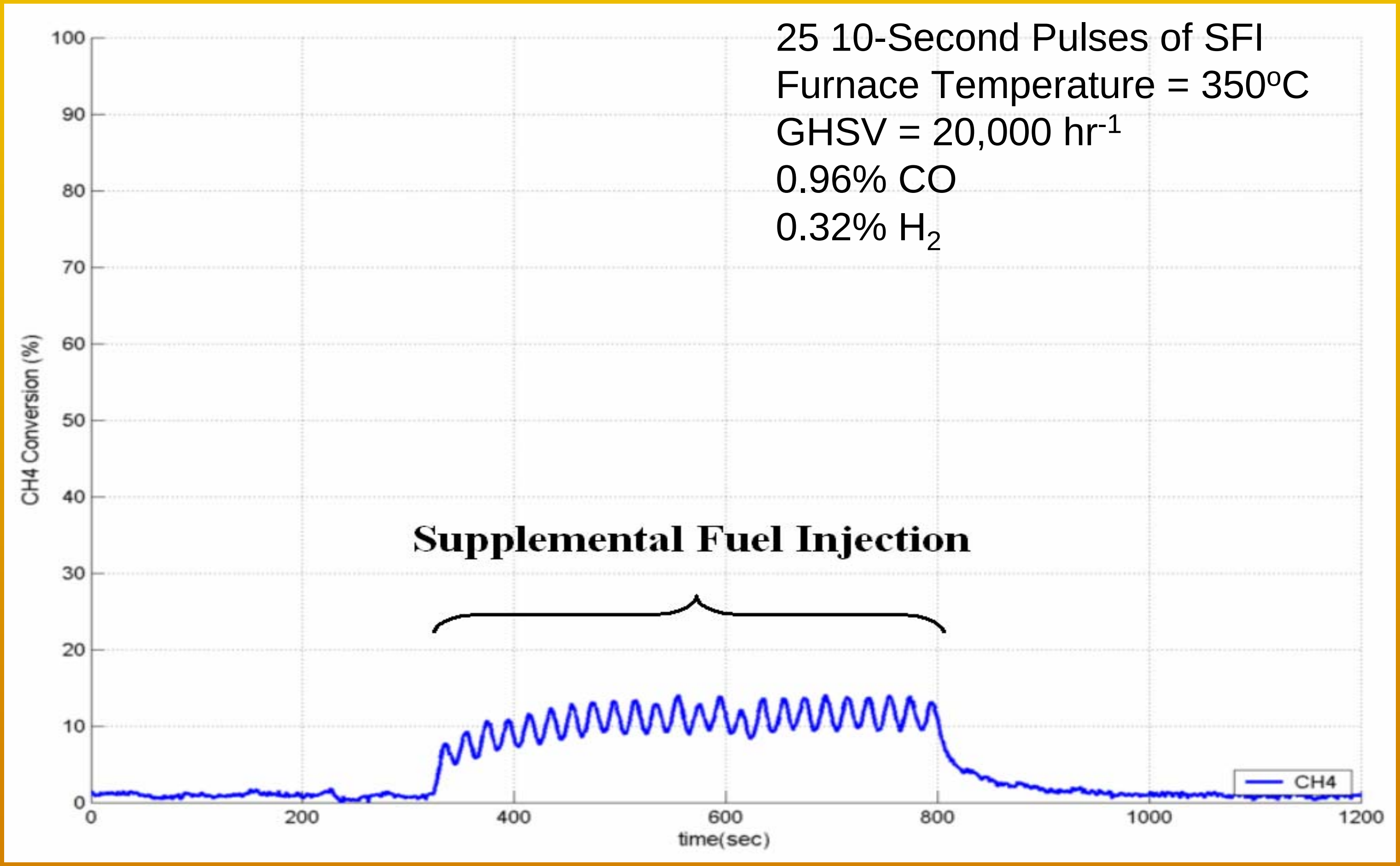
# Methane Conversion

Furnace Temperature = 550°C



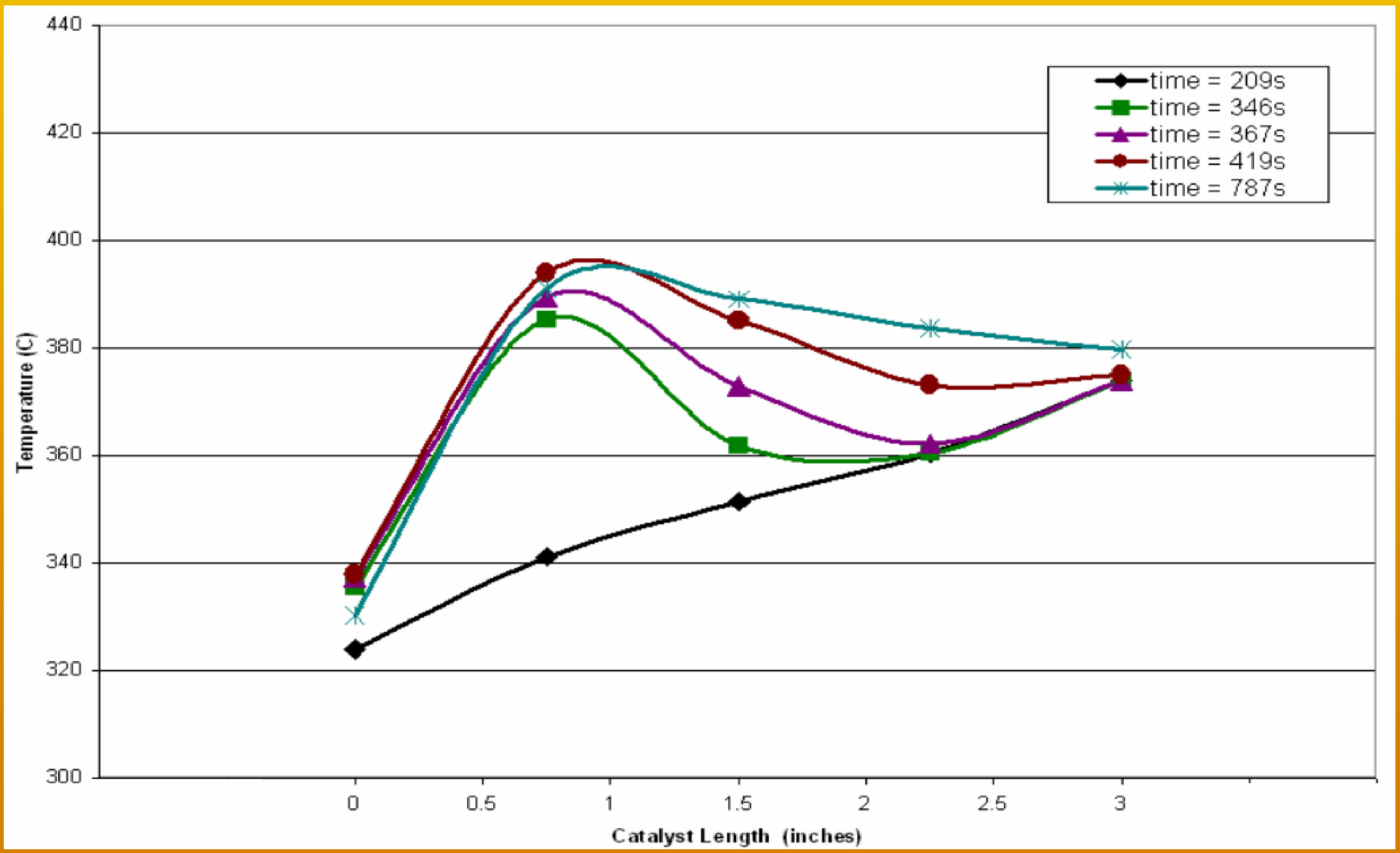
# Supplemental Fuel Injection

## Unidirectional Flow



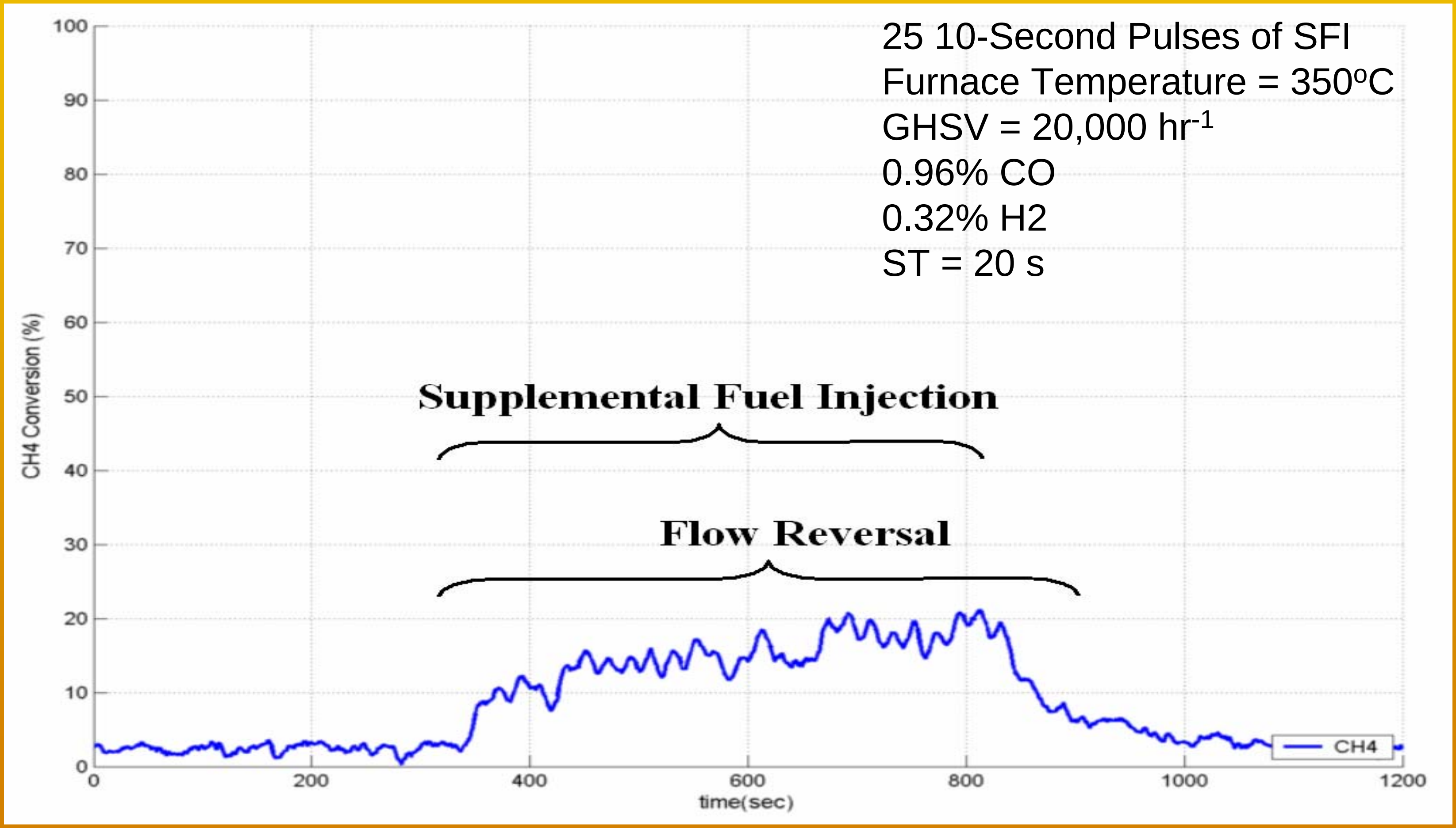
# Temperature Profile

Unidirectional Flow

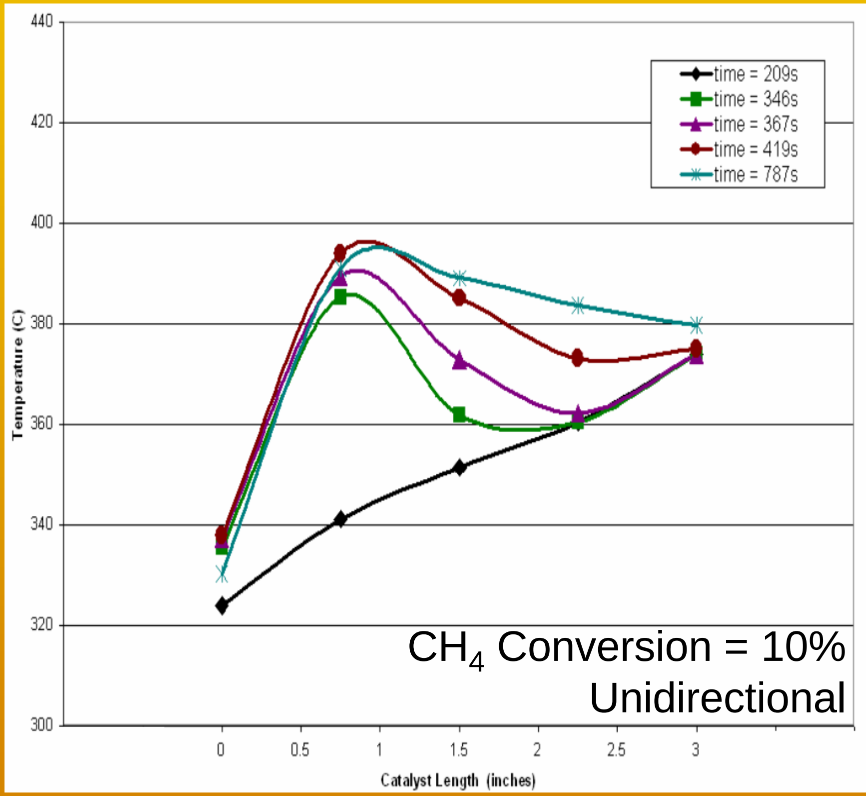


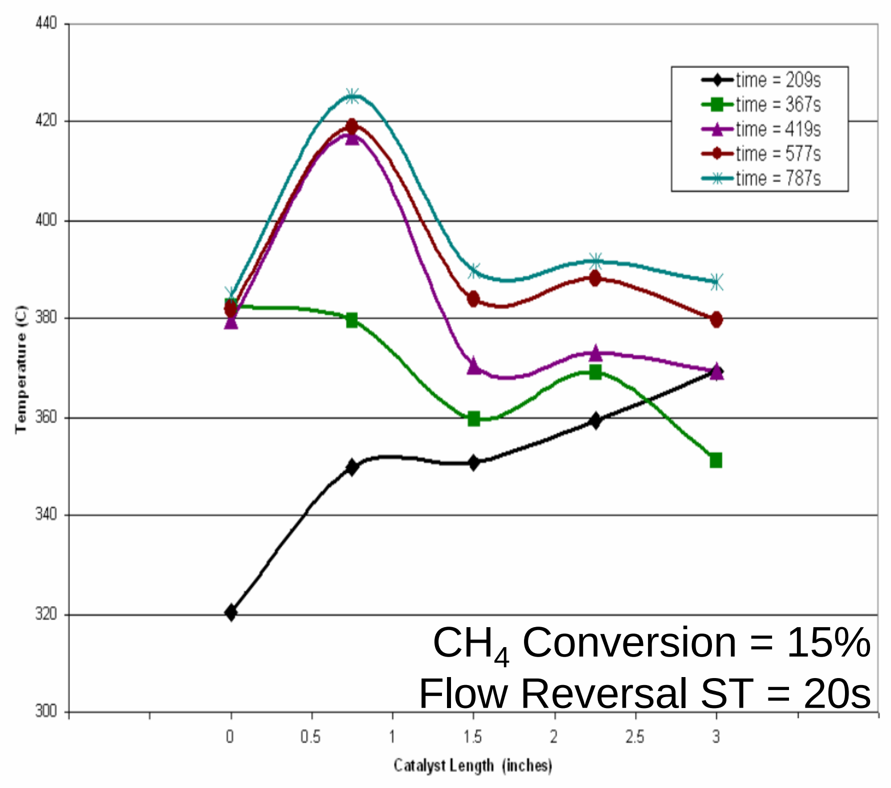
# Supplemental Fuel Injection

Reverse Flow



# Temperature Profile



# Conclusions

- $CH_4$ Conversion Improves with Flow Reversal

- At a GHSV of 20,000 $hr^{-1}$ Low Frequency Switching Times (30-45 Seconds) Produces a Maximum $CH_4$ Conversion

- At GHSVs of 40,000, 60,000, and 80,000 $hr^{-1}$ High Frequency Switching Times (10-20 Seconds) Produce a Maximum $CH_4$ Conversion

- Supplemental Fuel Injection Improves $CH_4$ Conversion

- Supplemental Fuel Injection with Flow Reversal Further Improves $CH_4$ Conversion

# Modeling of Reverse Flow Oxidation Catalyst

## Accomplishments

- A 1-D, Plug – flow heterogeneous model for reverse–flow oxidation catalyst has been developed.
- A code for the above model has been developed using Fortran.
- Simulation for different flow conditions is being done.
- Fine tune the simulated results and graphs.
- Simulate using the code for different temperatures with variable switching time and compare with the results from the experiments.

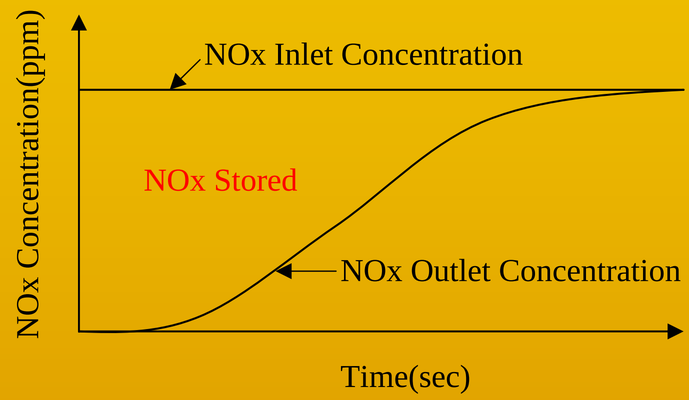
# Lean NOx Trap Evaluation and Optimization

**Accomplishments**

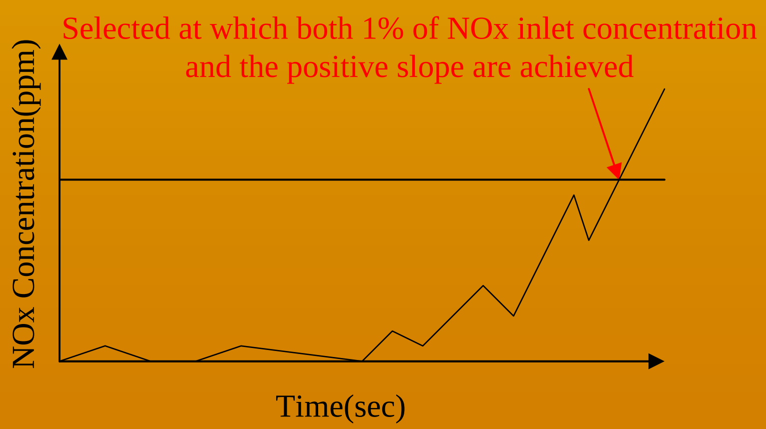
- Evaluation of LNT's storage capacity and breakthrough as function of temperatures (250-500C°) and space velocities (25,000 – 75,000 $hr^{-1}$)
- Evaluation of $H_2$ and CO as reducing agents
- Evaluation of regeneration of LNTs using lean and rich cycling and direct fuel injection

# Storage Capacity and Breakthrough

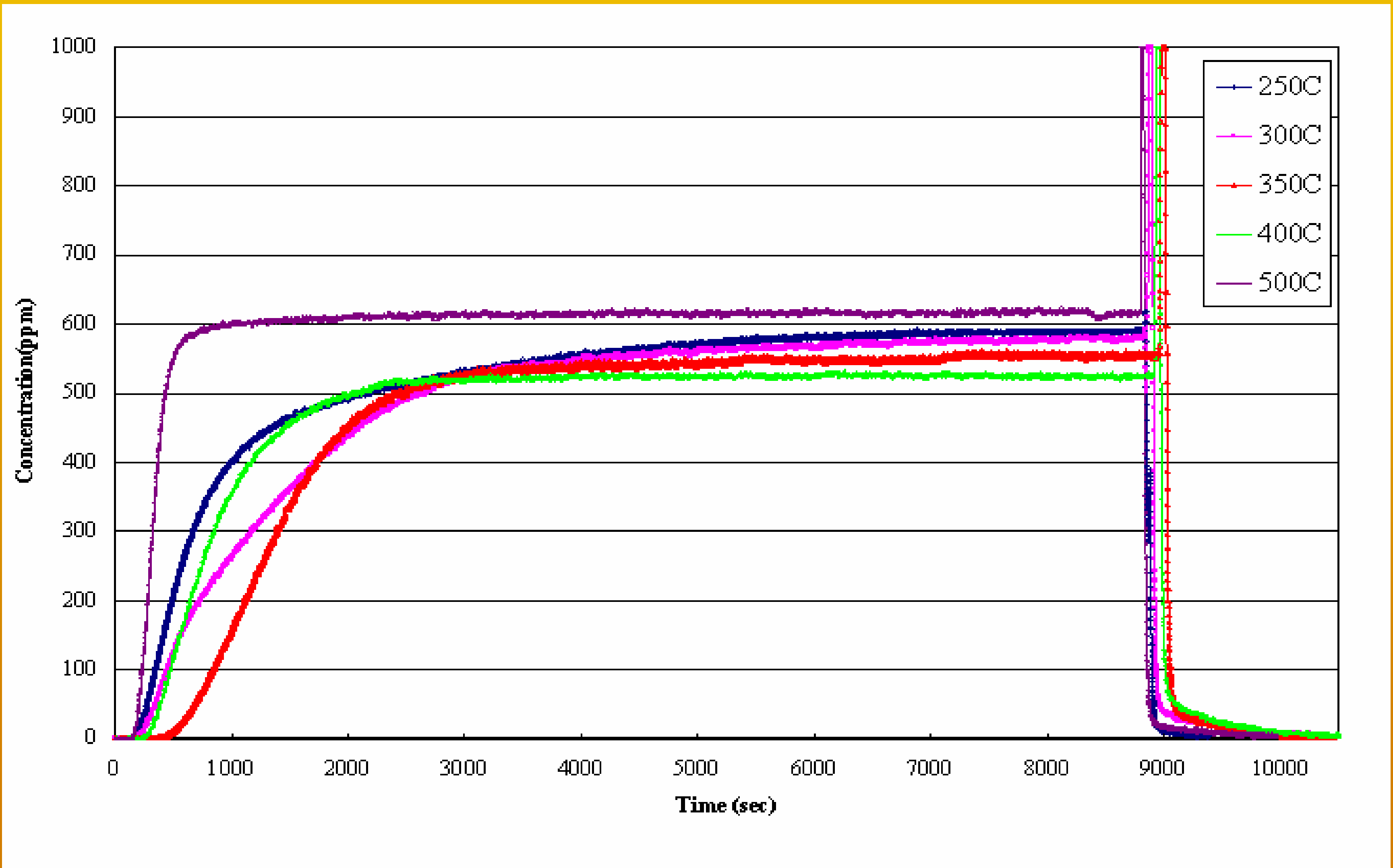
- The NOx storage capacity is directly proportional to the area between the NOx inlet concentration and the NOx outlet concentration trace.



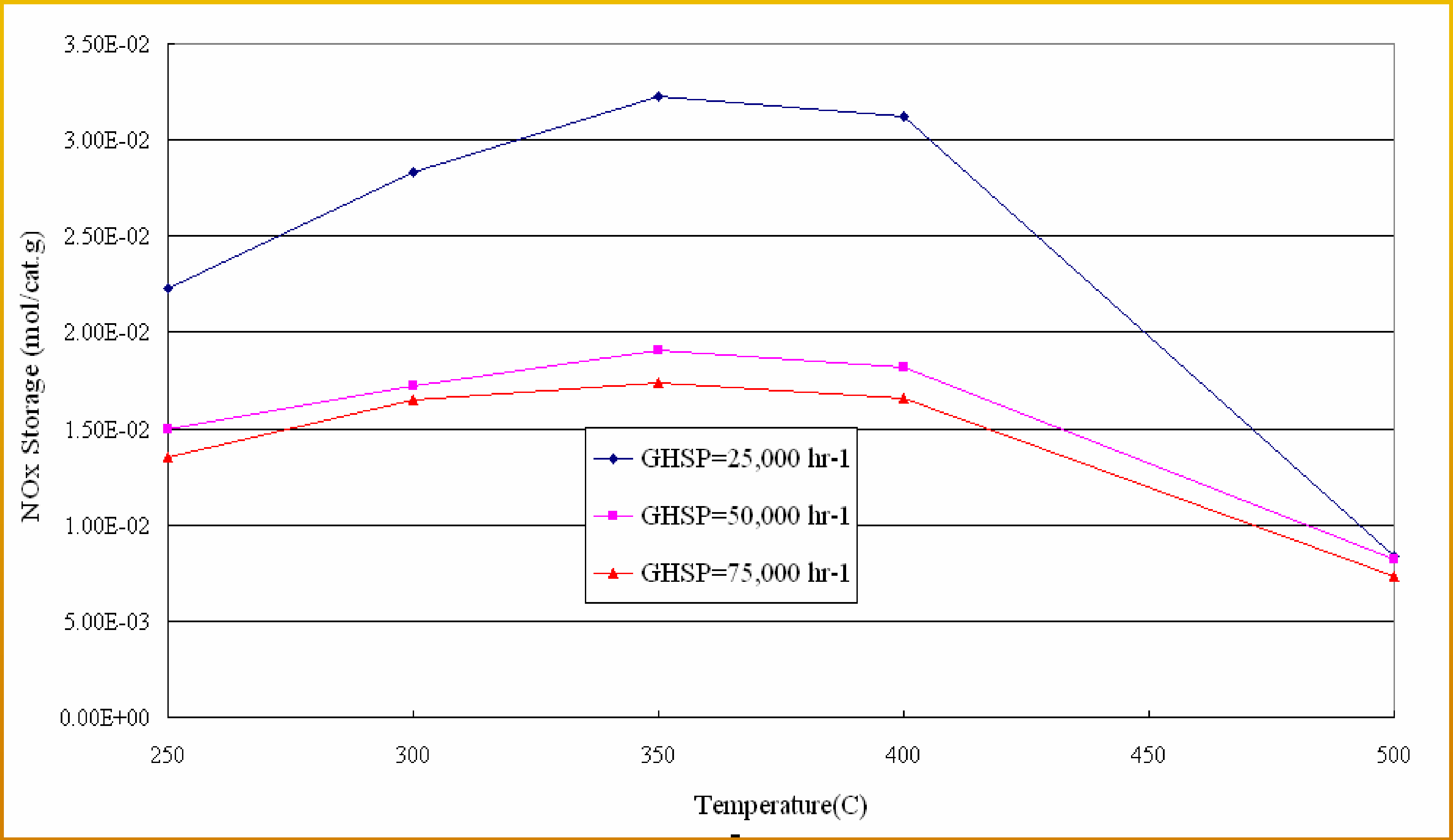

- Breakthrough time is the time after which there is an onset of NOx in the exhaust gas flowing from the outlet of LNT.



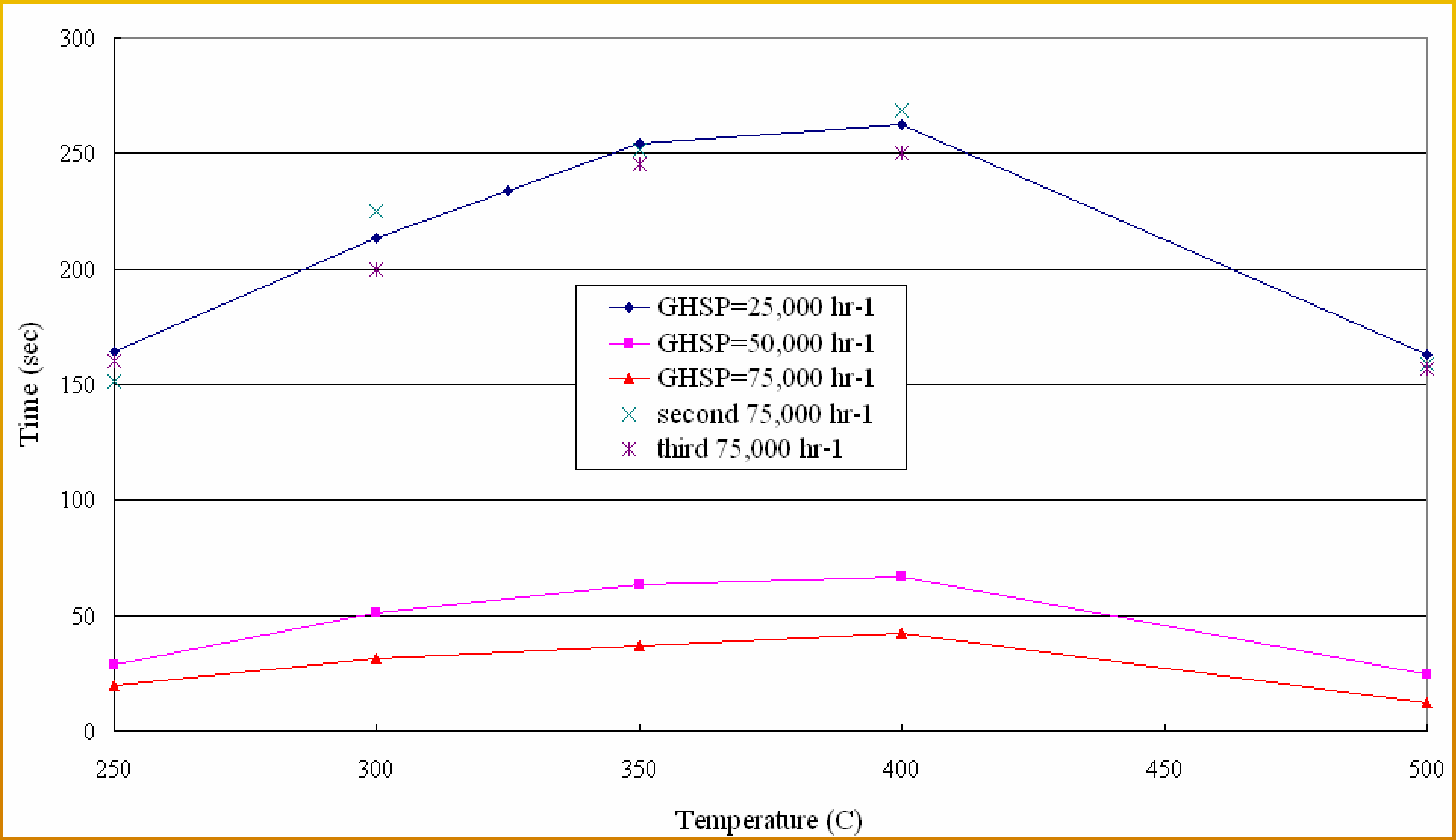
# Absorption Isotherms at a Gas Hourly Space Velocity of 25,000 $hr^{-1}$



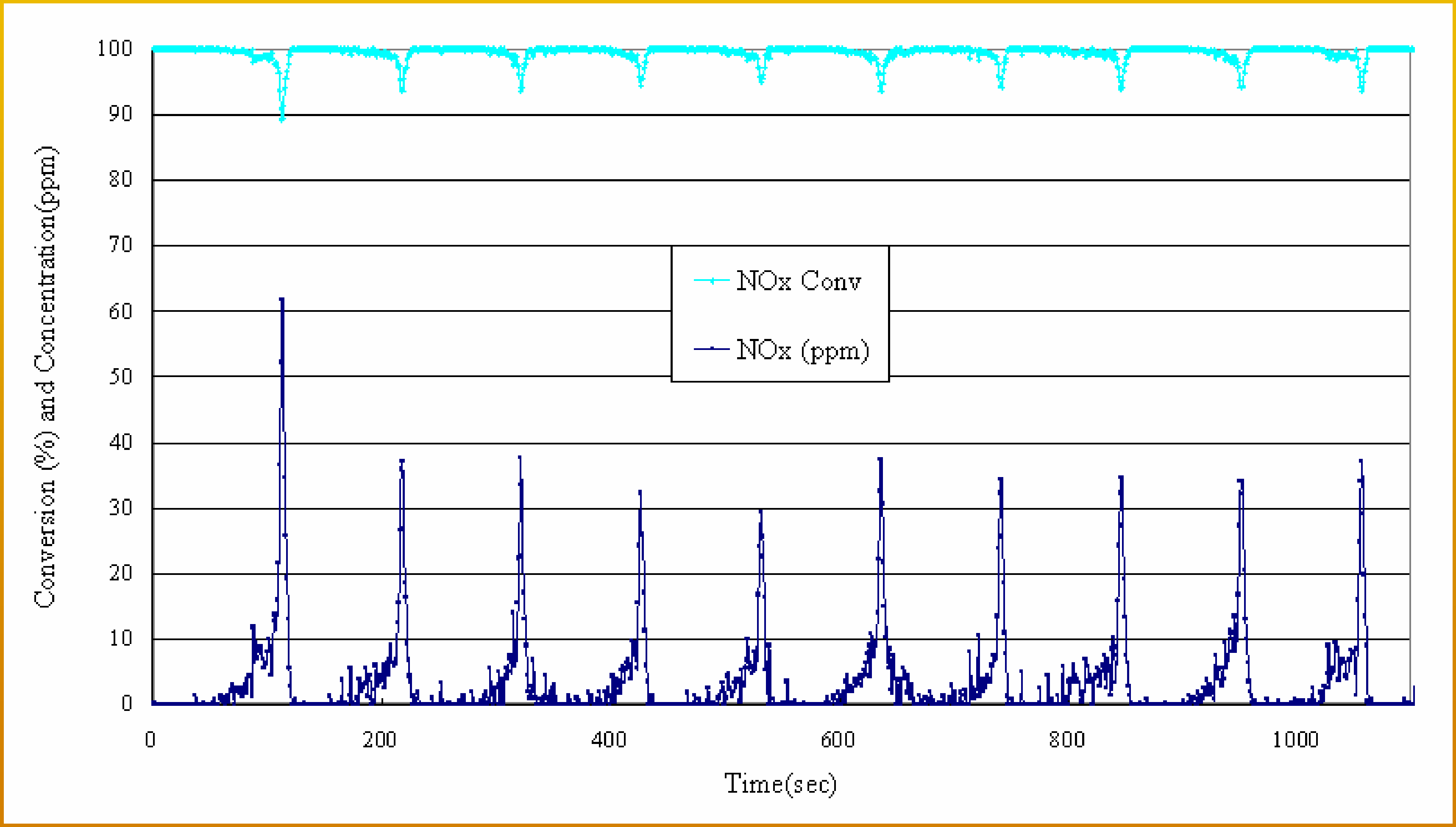
# LNT Storage Capacity



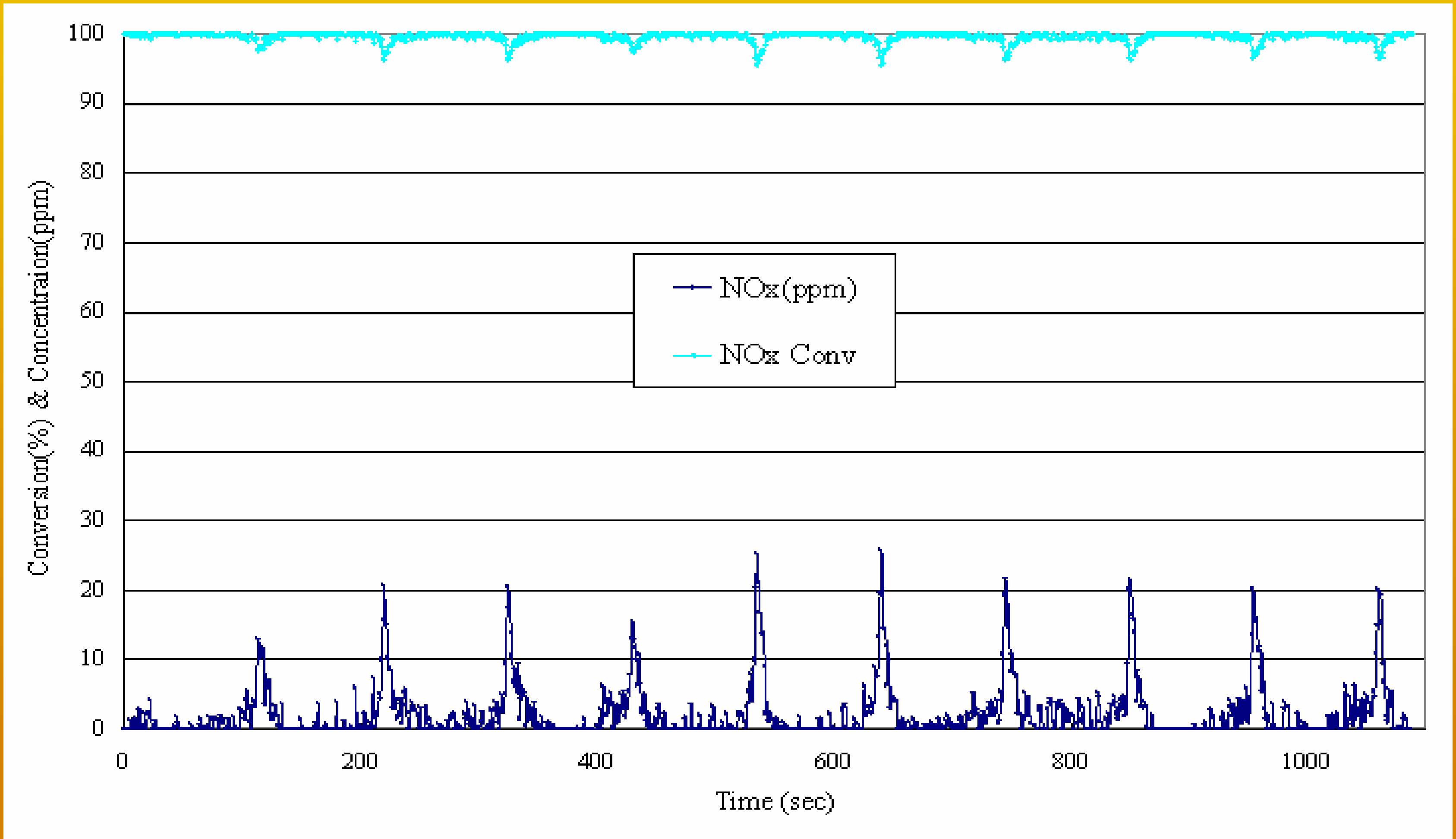
# LNT Breakthrough Time



# NOx Conversion for Cycling 100s lean and 5s rich with 500ppm of NOx Inlet Concentration ($4\%\ H_2$, T=350C° and SV=50,000hr$^{-1}$)



# NOx Conversion for Direct Fuel Injection with 500ppm of NOx Inlet Concentration
# (4% $H_2$, 100s lean, 5s rich, T=350C, and SV = 50,000hr$^{-1}$)



# Conclusions

- Optimum working temperature of LNT catalyst was found to be at 350˚ C at all space velocities
- Hydrogen was found to be a better reducing agent than carbon monoxide
- NOx conversion with direct fuel-injection and cycling lean and rich conditions are comparable

# Engine Scale Development

- Optimization of LNT configuration and control
- Development of reverse flow oxidation catalyst system and control

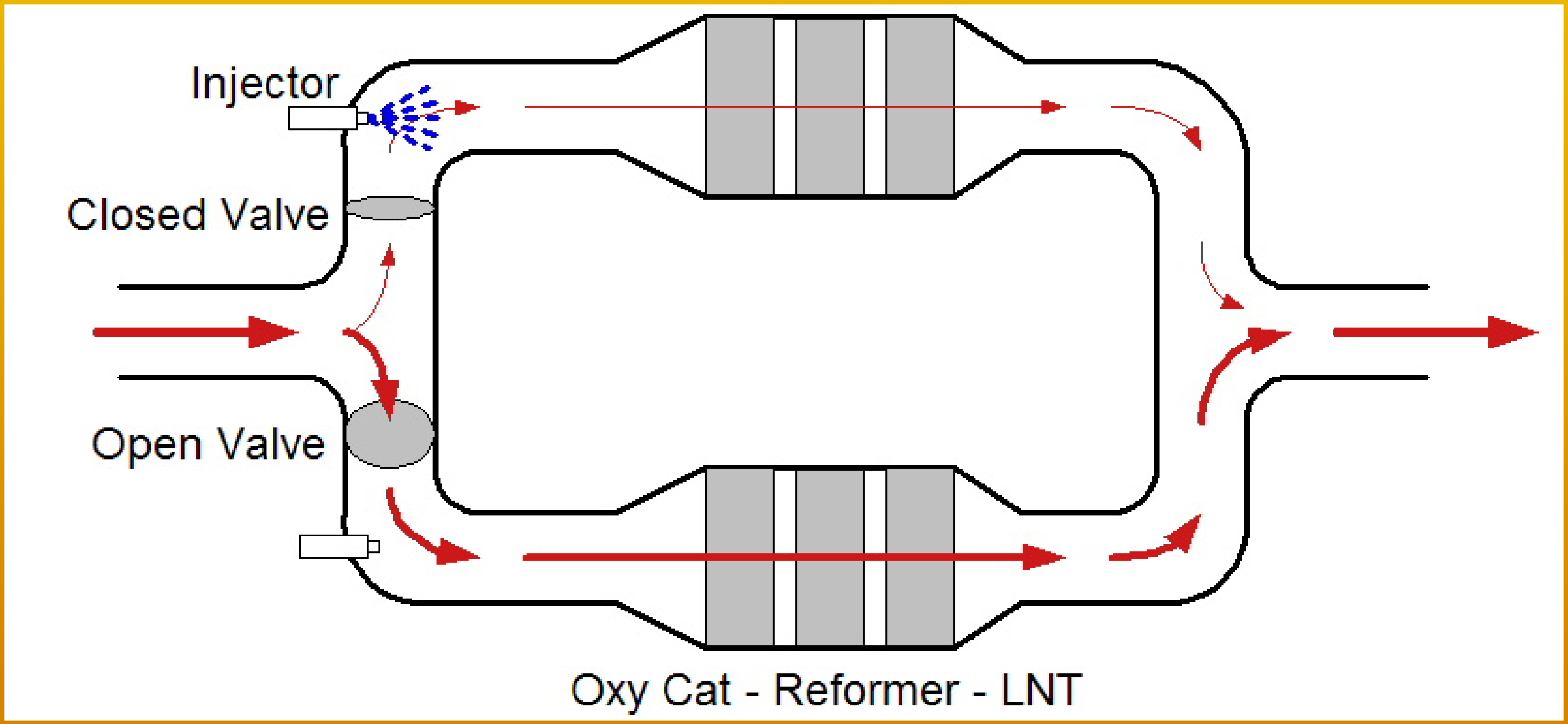
# Lean Burn Natural Gas Engine

**Collaboration with our colleagues at Oak Ridge National Laboratory**

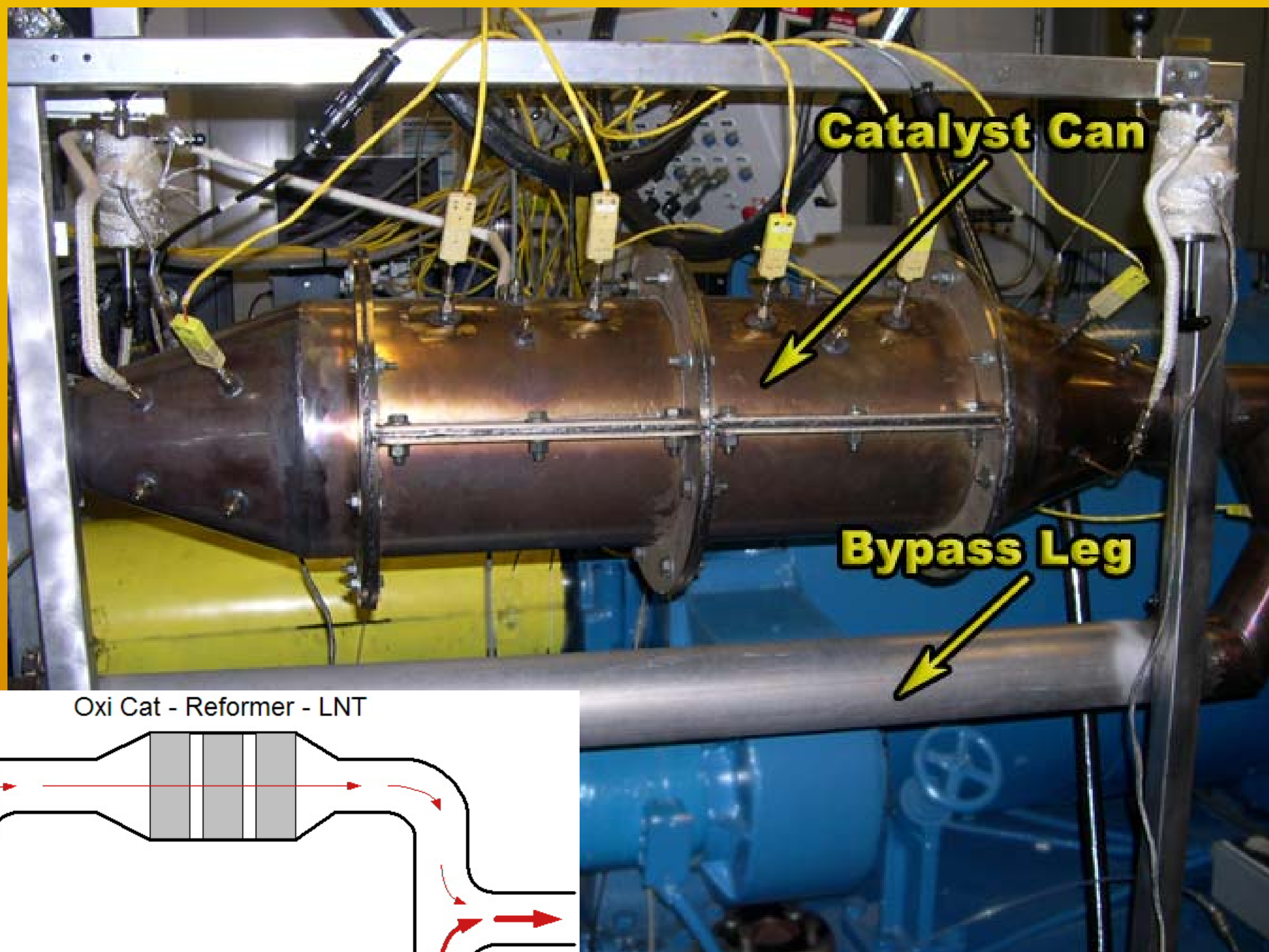
- Engine test cell located at National Transportation Research Center, a partnership between UTK and ORNL
- Baseline operating data for the engine and aftertreatment system shared between this project and ORNL's ARES project- "$NO_x$ Emissions Control for Natural Gas Engines and Natural Gas Vehicles"

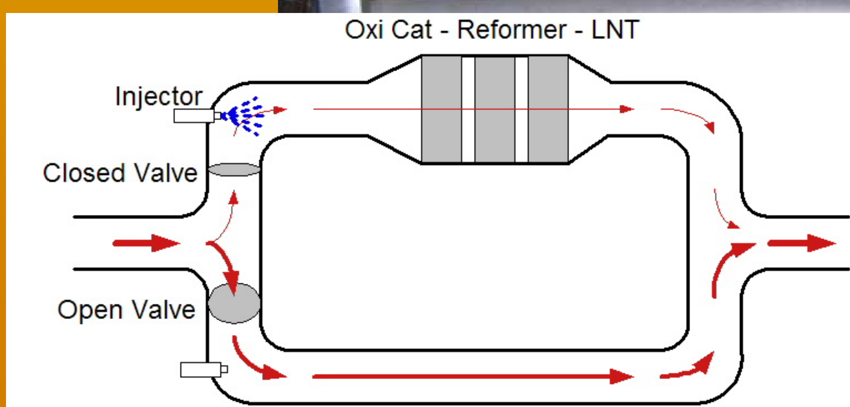
| C Gas Plus General Engine Data | | |
|---|---|---|
| Name | C Gas Plus | |
| Model | CG-280 | |
| Type | 4 Cycle; In-Line 6 Cylinder | |
| Bore x Stroke (mm) | 114 x 135 | |
| Displacement (L) | 8.3 | |
| **General Performance Data** | **Peak Power** | **Peak Torque** |
| Engine Speed (rpm) | 2400 | 1400 |
| Engine Power (kW) | 209 | 169 |
| Engine Torque (N-m) | 831 | 1153 |
| Inlet Air Flow (L/sec) | 293 | 205 |
| Exhaust Gas Flow (L/sec) | 817 | 539 |
| Exhaust Gas Temperature (C) | 643 | 587 |
| Nominal Fuel Consumption (kg/hr) | 47 | 34 |
| Inlet Air Restriction (mm H2O) | 445 | |
| Exhaust Restriction (mm Hg) | 102 | |

# Space Shared Multi-Chamber NOx Adsorber

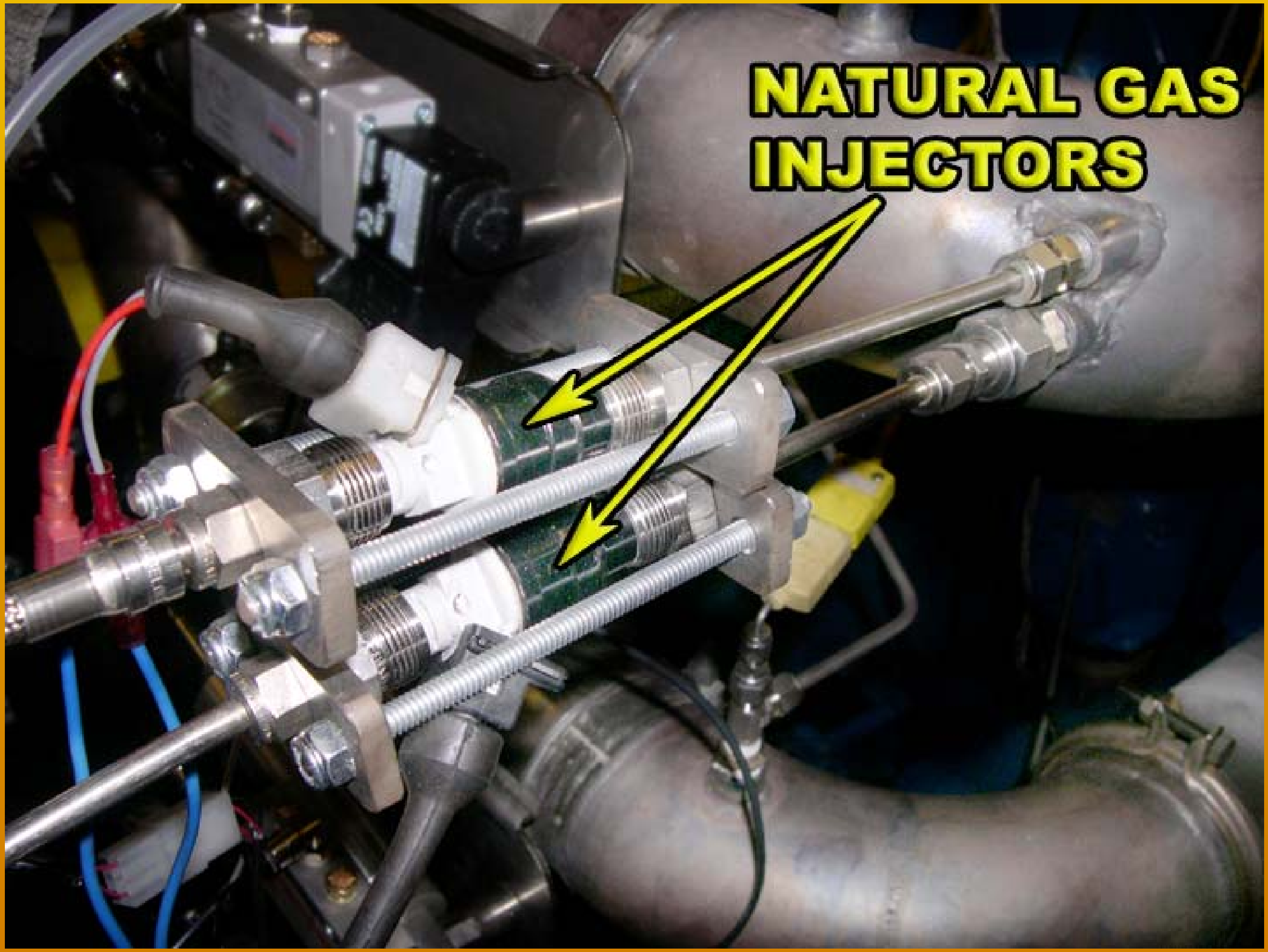


# Experimental Setup



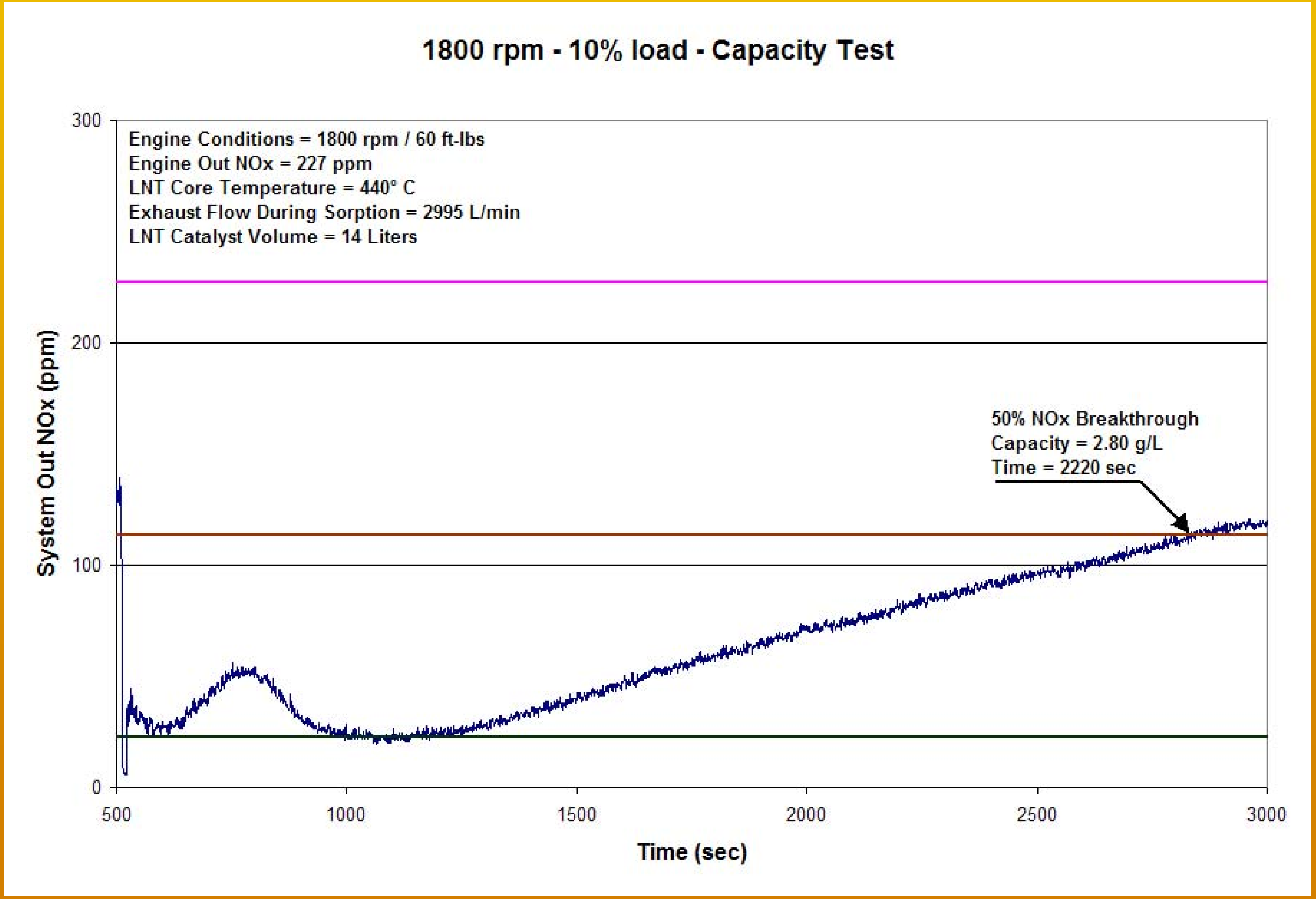



# Experimental Setup



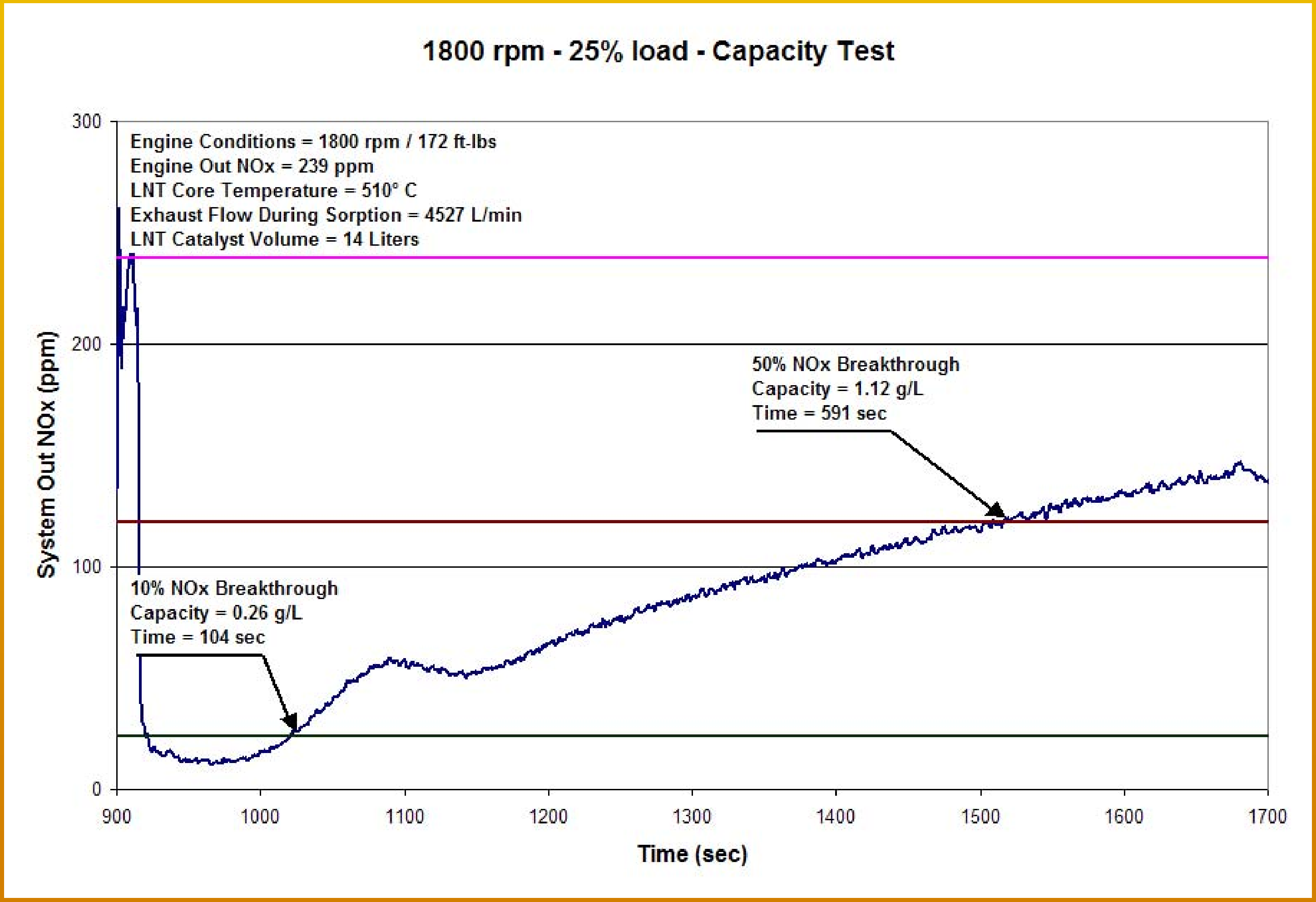
# Results

## NOx Adsorber Capacity

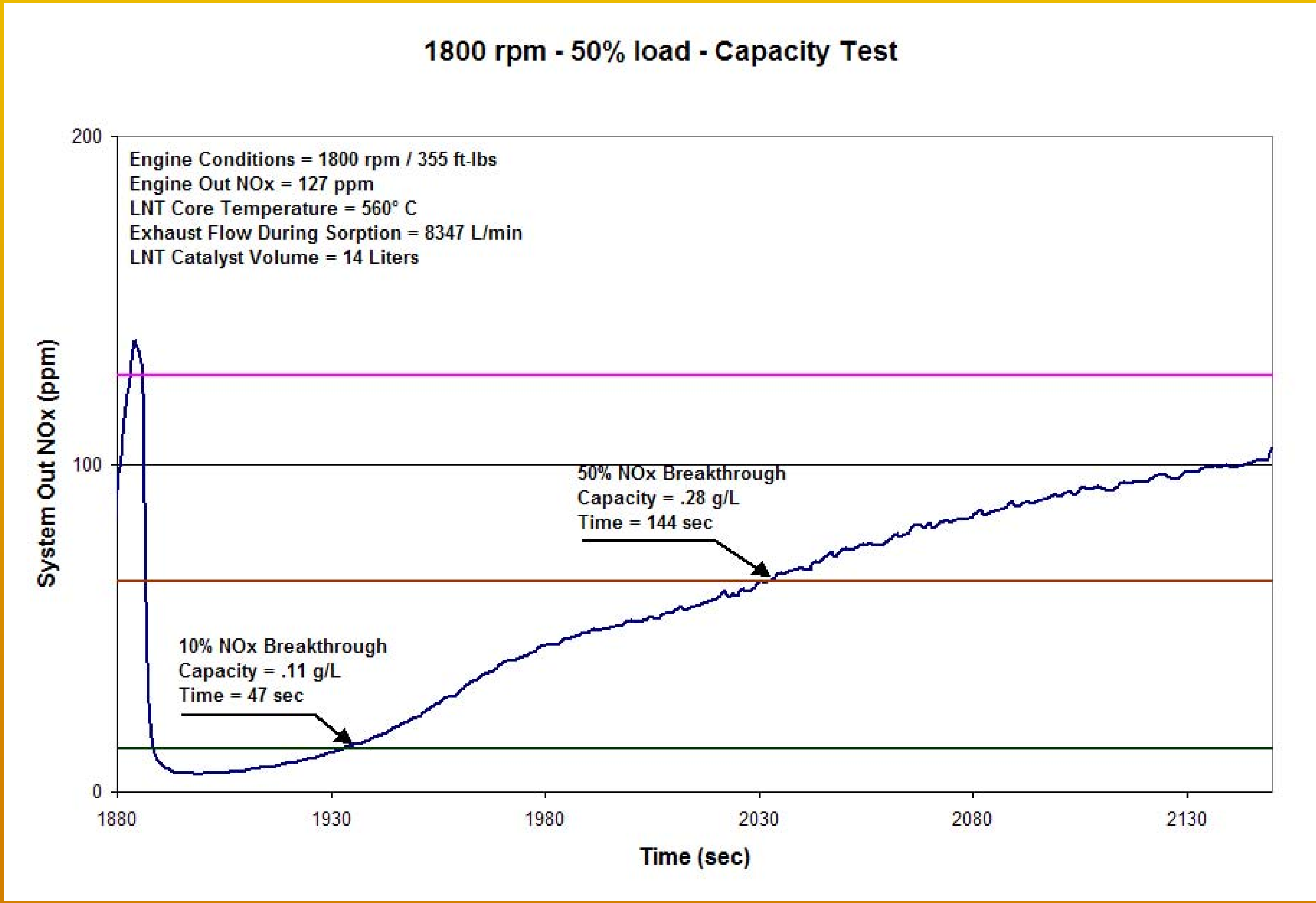


# Results

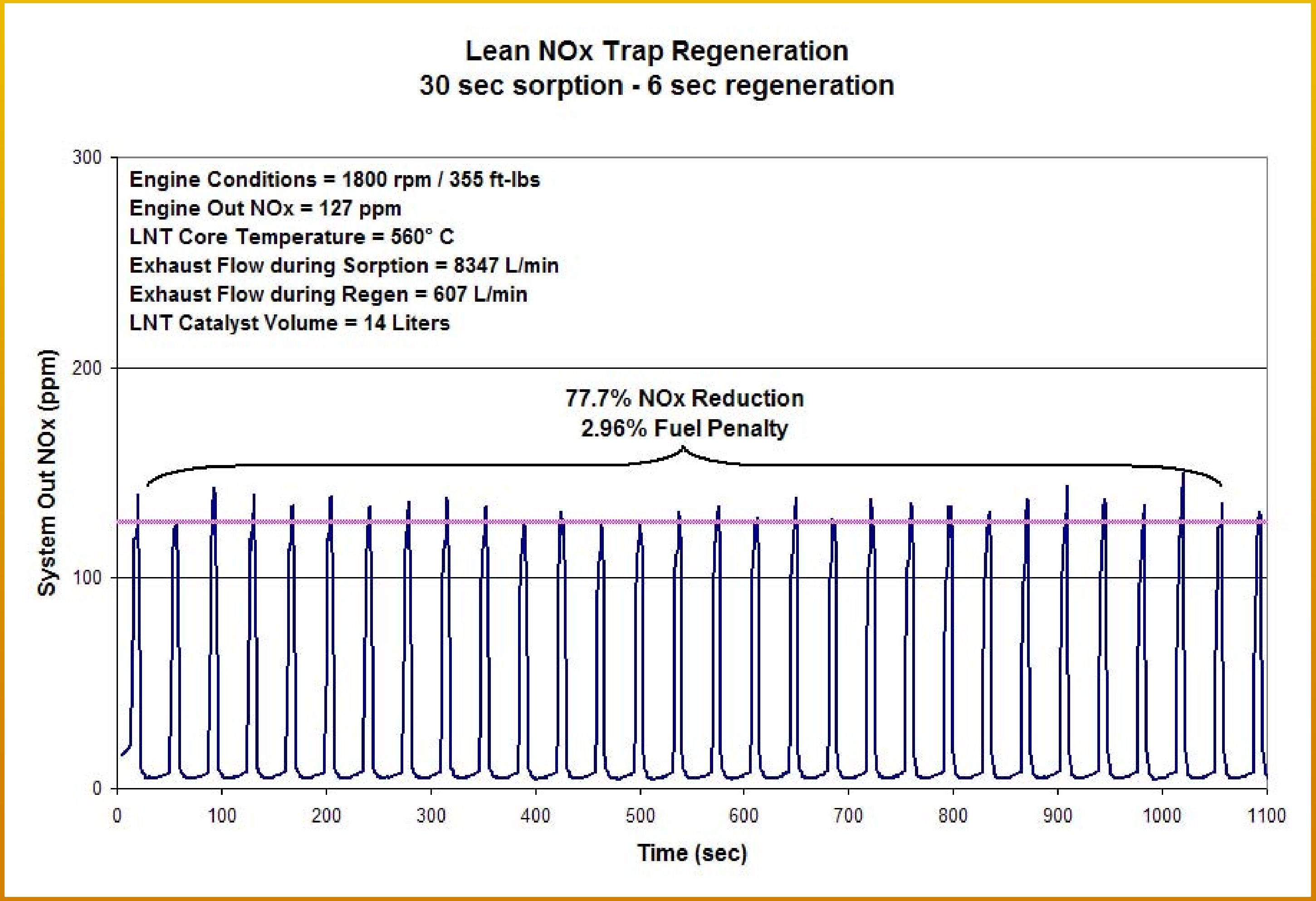
## NOx Adsorber Capacity



# Results
## NOx Adsorber Capacity

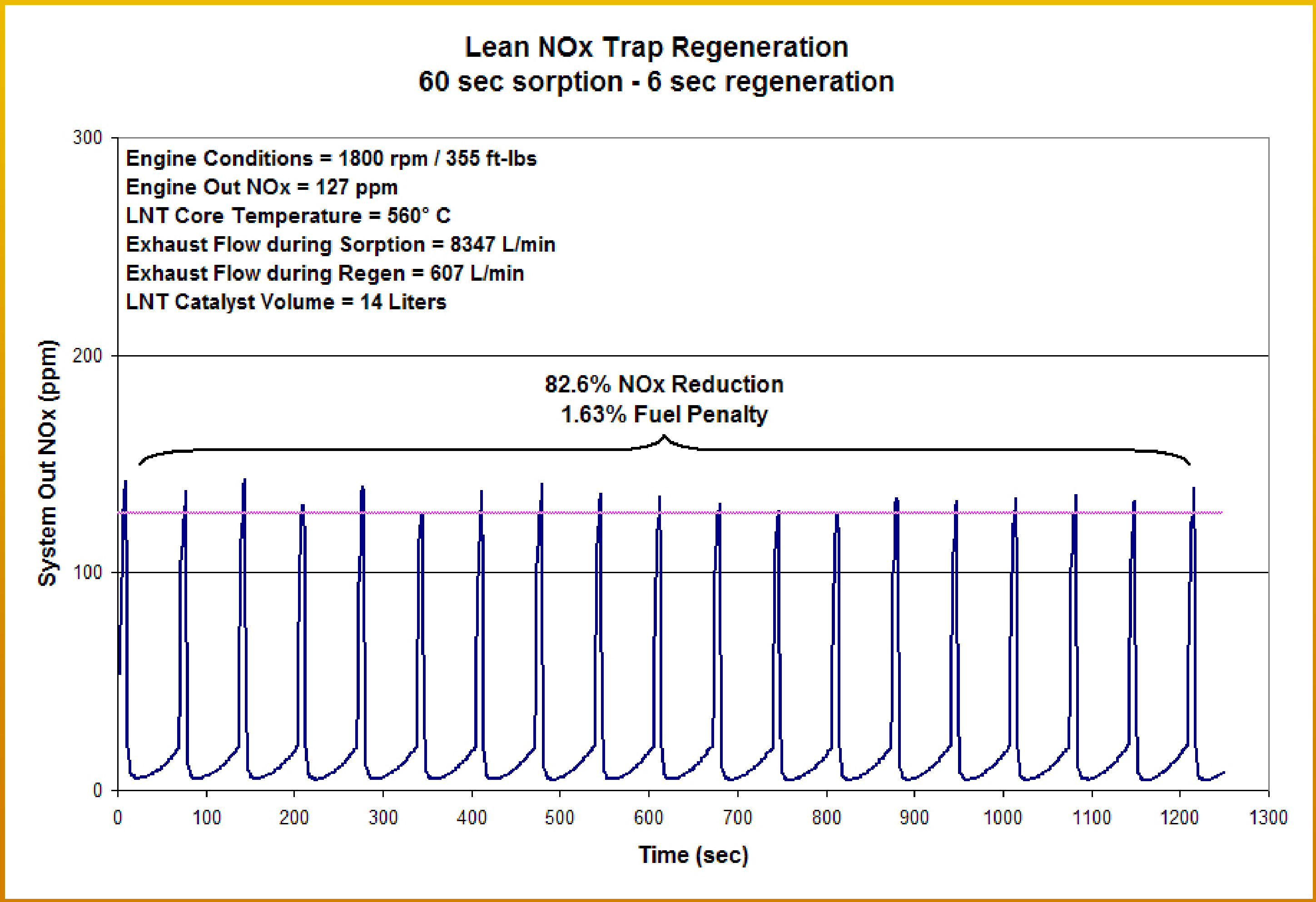


# Results
## NOx Adsorber Regeneration

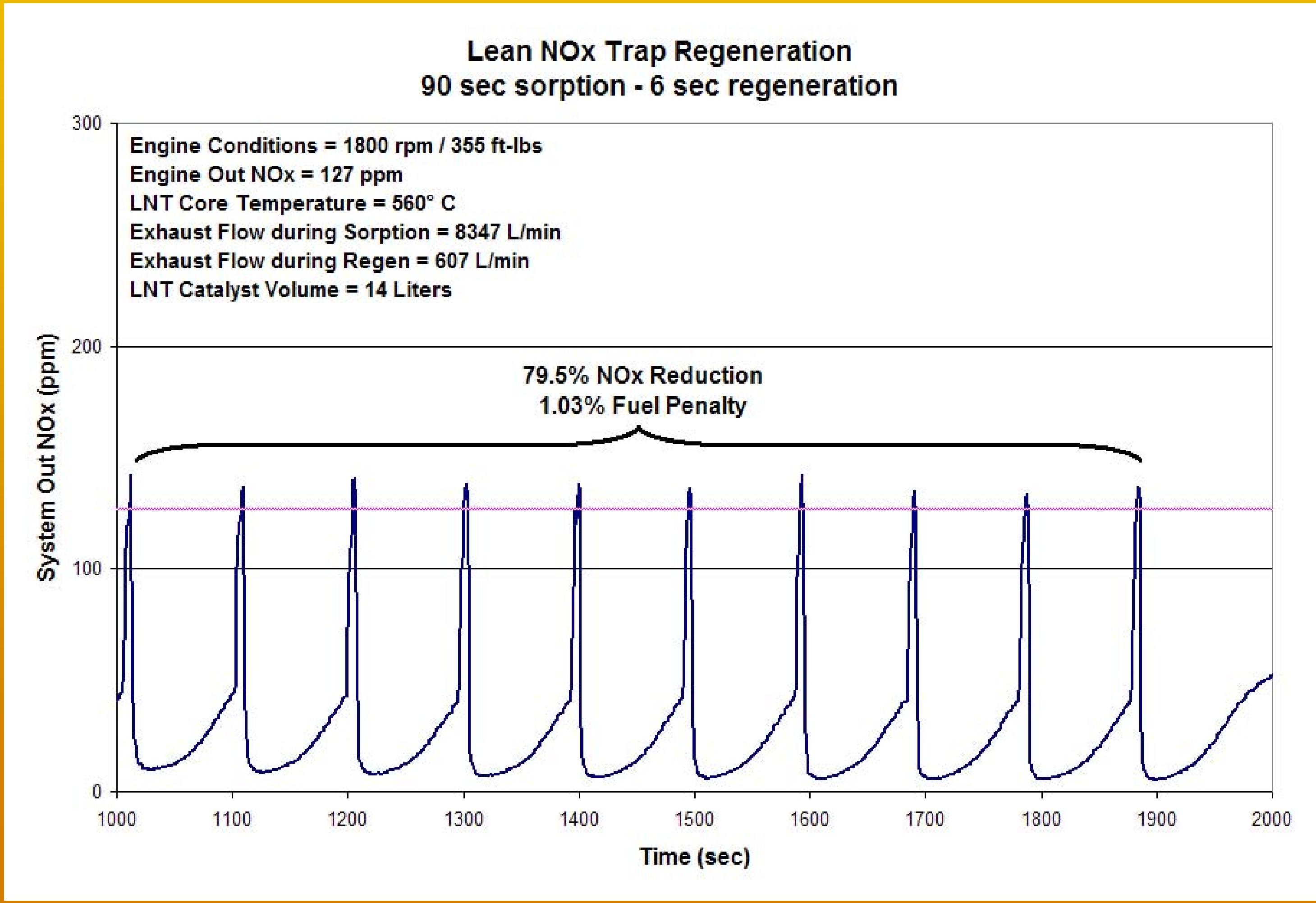


# Results

## NOx Adsorber Regeneration



# Results
## NOx Adsorber Regeneration

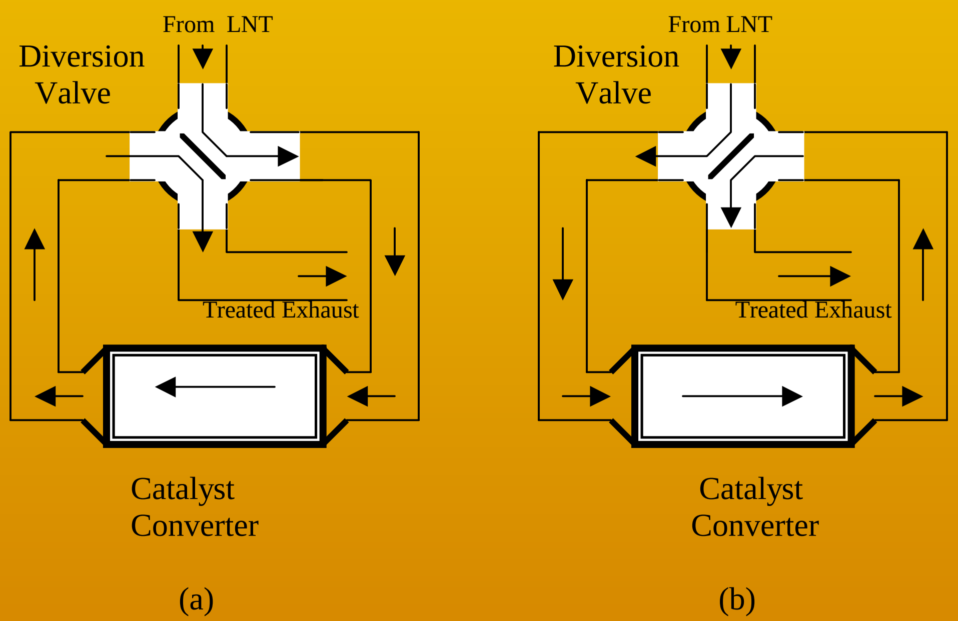


# Lean $NO_x$ Trap System

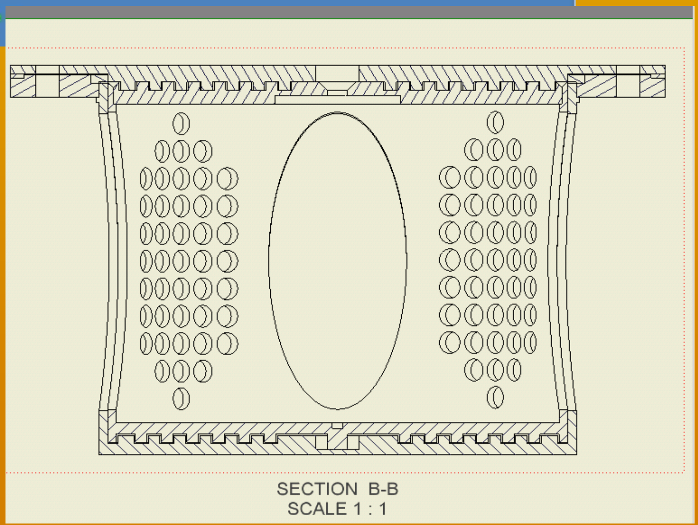
- Test $NO_x$ reduction in a dual leg system
- Optimize dual leg LNT system on time based regeneration (open-loop)
- Observe and isolate key parameters that will enable closed loop operation
- Optimize closed loop system to reach ARES goal of 0.1 g/bhp-hr engine out $NO_x$

# Reverse Flow Catalyst System

- Engine testing will utilize the Cummins 8.3L NG engine test bed at NTRC facility
- Initially the LNT section will be by-passed to isolate key parameters
- Testing will focus on maintaining optimum temperature profile for high efficiency oxidation



# Reversing Valve

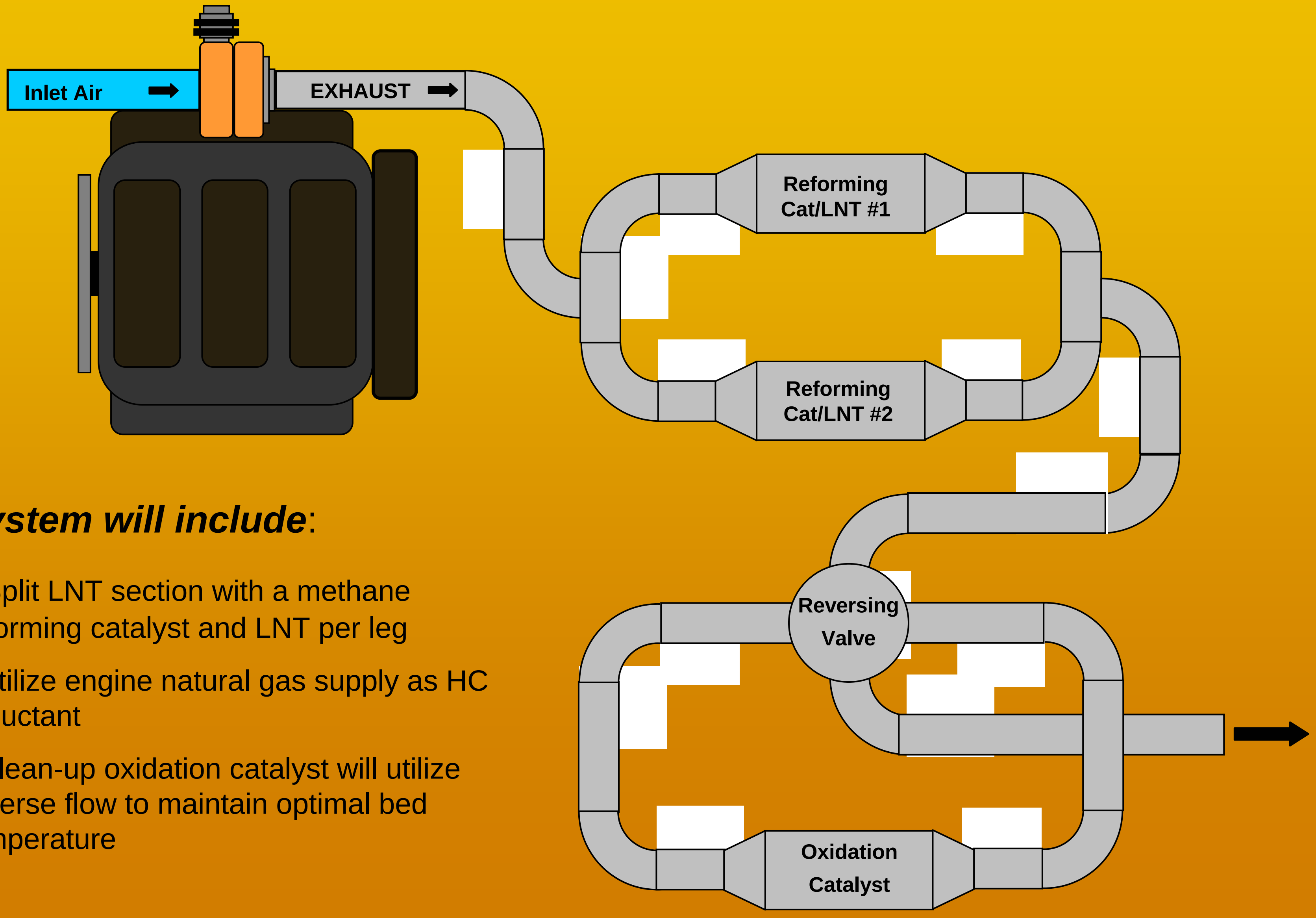



# Reversing Valve

# Future Work

- Complete fabrication of the four-way reversing valve
- Engine testing and optimization of the reverse flow catalyst system
- LNT control development and regeneration optimization
- Complete reverse flow catalyst and LNT system integration and optimization

# Complete LNT and Reverse Flow System

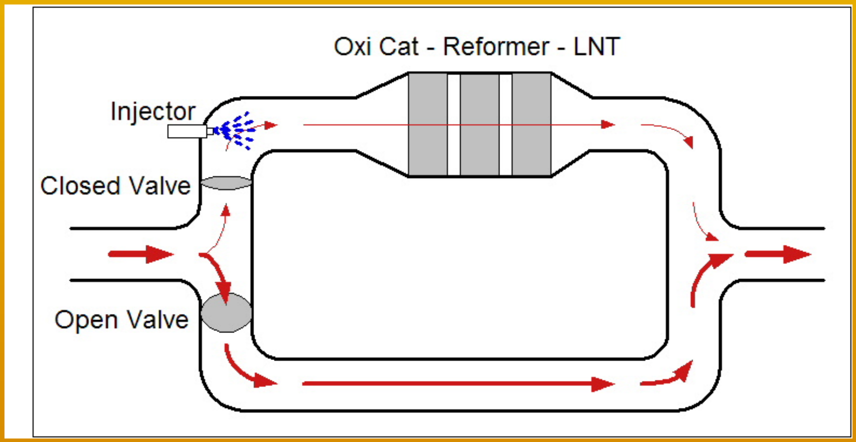



***System will include***:

- Split LNT section with a methane reforming catalyst and LNT per leg
- Utilize engine natural gas supply as HC reductant
- Clean-up oxidation catalyst will utilize reverse flow to maintain optimal bed temperature

# Complete System Optimization

- UTK/ORNL ARES work to date has been done on a single leg system with a by-pass
- Current phase is modeling the optimal catalyst volume (multiple legs) required to minimize fuel penalty while meeting ARES goal
- Final phase will test complete multi-leg system with intelligent control system

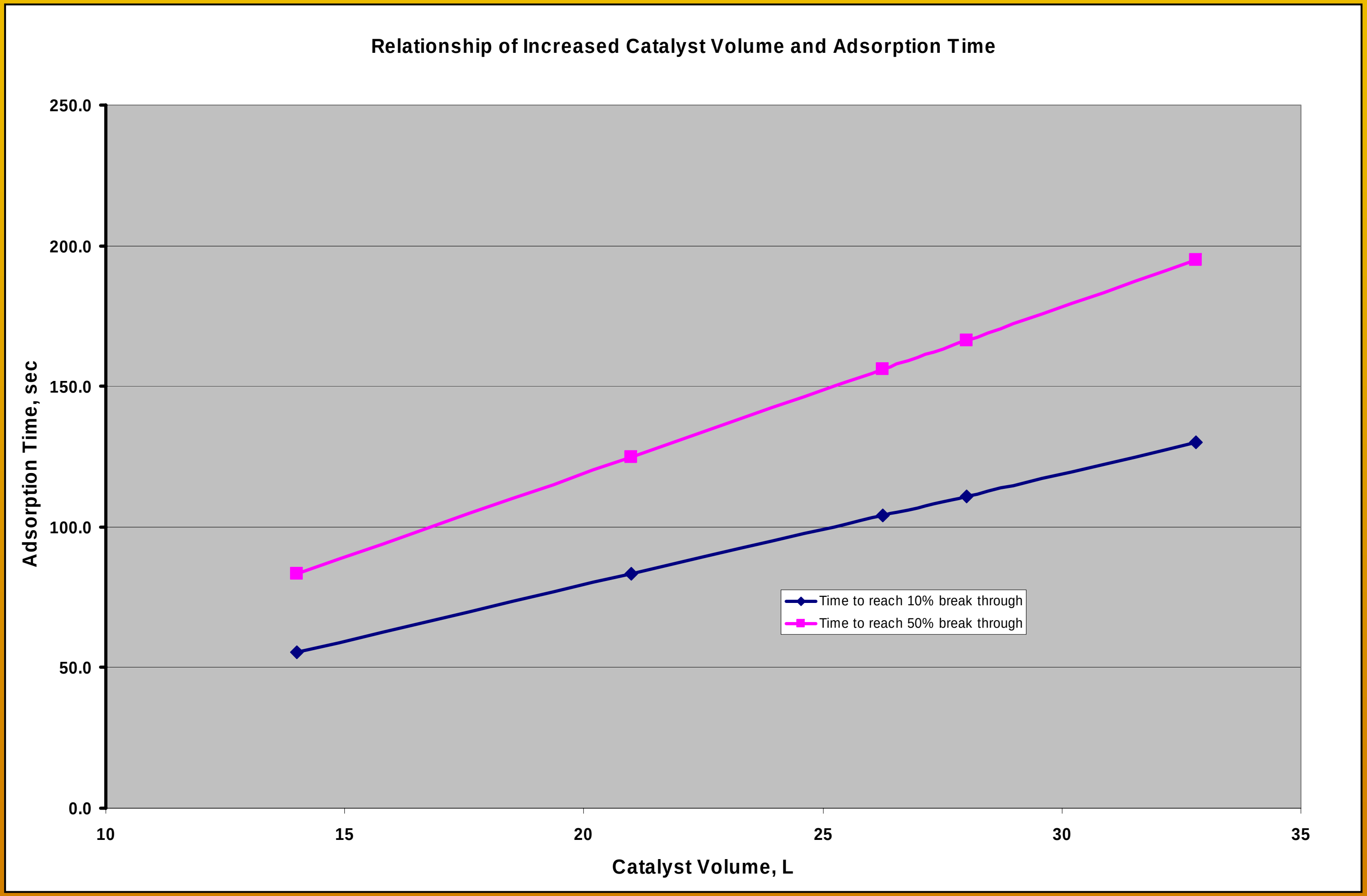


# Effects of Catalyst Volume

- Increased catalyst volume increases adsorption time, which decreases supplemental fuel frequency and use
- Increased catalyst volume through multiple legs can slightly reduce catalyst temperature (off-line cooling effect)
- Increased catalyst volume and reduced catalyst temperature will optimize the trapping efficiency

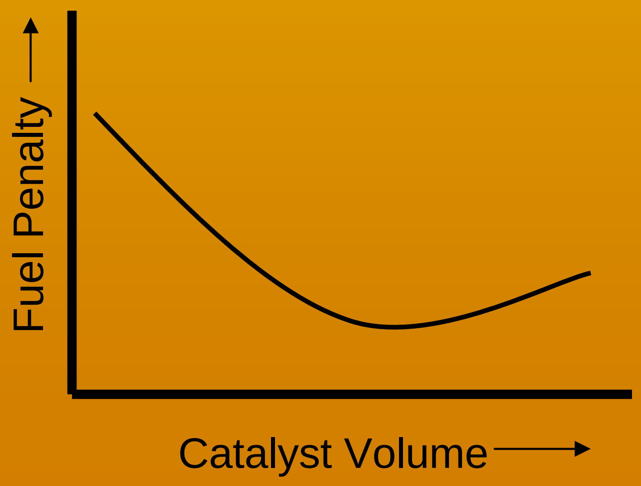
* Plots based on bench flow data

# Storage Capacity



# Optimize Catalyst Volume

- Model investigating the temperature and fueling effects based on increased catalyst volume
- Model will also outline parameters to investigate in complete system testing




i. Catalyst Temperature

ii. NOx Rate

iii. Fuel Rate/Oxygen Depletion

iv. Methane Utilization/$H_2$ Creation

v. Regen Flow Rate

# UTK Intelligent NOx Reduction Control System

*Time Based Control*

- Regen/Adsorb Cycle controlled by time period developed from laboratory data collected in ORNL study
- Catalyst temperature, fuel rate, and NOx reduction were optimized based on laboratory observations

*Feedback Loop Control*

- Based on intelligence gained in ORNL and UTK bench flow reactor work, control system will monitor key parameters i.e. NOx engine out rate, catalyst temperature
- Based on stored maps of catalyst storage rate, the control system will initiate regen to optimize methane utilization, $H_2$ creation, and NOx conversion while minimizing fuel penalty

# Acknowledgements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  - James E. Parks II
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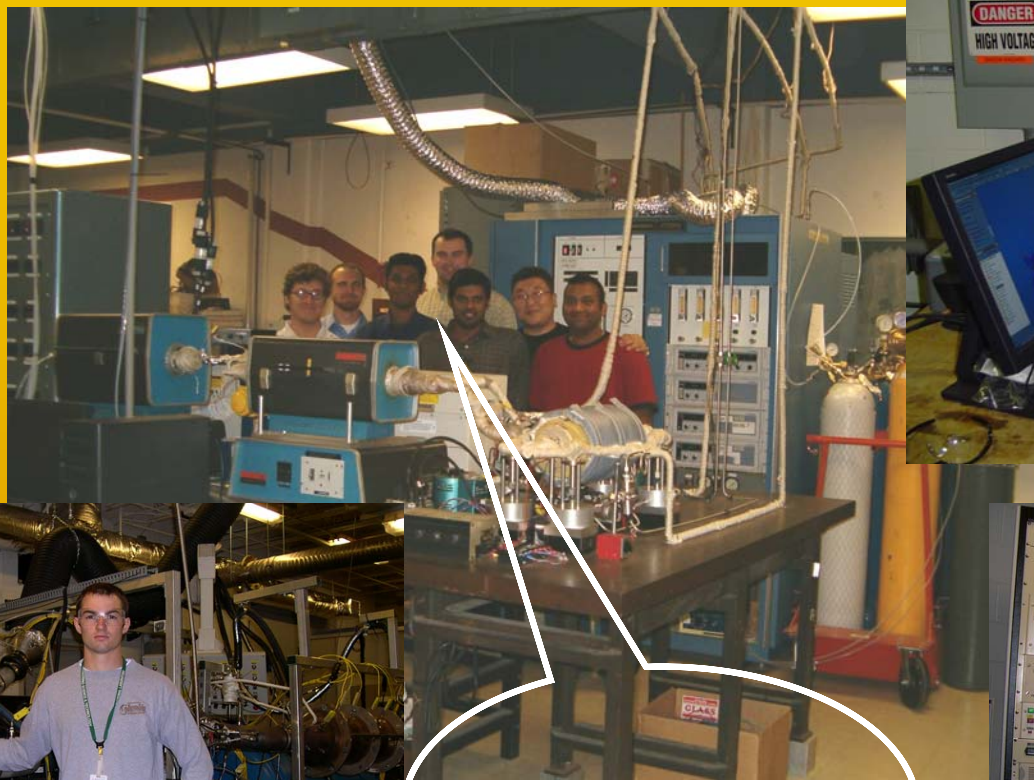
    - Vitcheslav Naoumov
    - Doug Ferguson
    - *Ming Zheng
  - Graduate Students
    - Scott Smith
    - Barath Raghavan
    - Kim Hakyong
    - Balaji Ramamurthy
    - John Miller
    - Aaron Williams




Questions?

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